ASD-TDR-7-945 (II)

LINER FOR EXTRUSION BILLET CONTAINERS

Interim Technical Documentary Progress Report Nr ASD-TDR-7-945 (II)

5 June 1962 - 5 December 1962

Report on Phase I

Basic Industry Branch
Manufacturing Technology Laboratory
Aeronautical Systems Division
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

ASD Project Nr 7-945

Two shrink-fitted compound sleeve assemblies have been designed to supply required support for use of solid ceramic, ceramic-coated metal, and elevated temperature metal extrusion liners, at stem pressure of 180,000 psi. Liner and sleeve machining and shrink-fitting data are supplied. Assemblies are designed for rapid removal from container in event of liner failure. A device has been designed for the rapid heating and accurate assembly of sleeves to be shrink fitted.

(Prepared under Contract AF 33(657)-8784 by Armour Research Foundation, Chicago, Illinois, S. A. Spachner).

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FOREWORD

This Interim Technical Documentary Progress Report covers the work performed under Contract AF 33(657)-8784 from 5 June 1962 to 5 December 1962. It represents a summary report on Phase I, "Design and Construction of New Billet Containers." It is published for technical information only and does not necessarily represent the recommendations, conclusions or approval of the Air Force.

This contract with Armour Research Foundation, Chicago, Illinois, was initiated under Manufacturing Methods Project 7-945, "Liner for Extrusion Billet Containers." It is being accomplished under the technical direction of T. S. Felker of the Basic Industry Branch, ASRCT, Manufacturing Technology Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio

Dr. Sheldon A. Spachner of the Foundation's Metals and Ceramics Research Division is the metallurgist in charge and performed all the container calculations. Others who cooperated in the research were Michael Hnatusko and Roy E. Reinholds, Project Technicians; Jack V. Smith, Tool Designer; R. G. Sturm, Project Consulting Engineer; and Harry Schwartzbart, Assistant Director, Metals and Ceramics Research. This report has been given the Foundation number ARF-B244-6.

The primary objective of the Air Force Manufacturing Methods Program is to develop on a timely basis manufacturing processes, techniques and equipment for use in economical production of USAF materials and components. The program encompasses the following technical areas:

Rolled Sheet, Forgings, Extrusions, Castings, Fiber and Powder Metallurgy; Component Fabrication, Joining, Forming, Materials Removal; Fuels, Lubricants, Ceramics, Graphites, Nonmetallic Structural Materials; Solid State Devices, Passive Devices, Thermionic Devices.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated.

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ABSTRACT - SUMMARY
Interim Technical Documentary Report

ASD-TDR-7-945 (II)
December 1962

LINER FOR EXTRUSION BILLET CONTAINERS

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Armour Research Foundation

Two shrink-fitted compound sleeve assemblies have been designed to supply required support for use of solid ceramic, ceramic-coated metal, and elevated temperature metal extrusion liners, at stem pressures of 180,000 psi. Liner and sleeve machining and shrink-fitting data are supplied. The first assembly develops required support for ceramic liners and other materials which have high compressive strength and low tensile strength. The second assembly provides required support for materials which have modest elastic strain capability and/or strength in both tension and compression.

A device has been designed for the rapid heating and accurate assembly of sleeves to be shrink-fitted.

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LINER FOR EXTRUSION BILLET CONTAINER

Report on Phase I:

Design and Construction of New Billet Container

I. INTRODUCTION

The objective of this effort is a design of suitable support tooling to permit use of solid ceramic, ceramic coated metal, and elevated temperature metal extrusion liners, at stem pressures of 180,000 psi. This has been accomplished by design of two compound sleeve assemblies. The first assembly supplies required support for ceramic liners and other materials which have high compressive strength and low tensile strength. The second assembly supplies required support for materials which have approximately equal, though modest, elasticity and strength in both tension and compression. This design minimizes both ductility and strength requirements to permit use of a larger variety of materials.

Both assemblies have been designed to use minimal amount of liner material, which may be relatively expensive, and to permit rapid liner interchangeability in the container in event of failure. Design data and stress calculations are presented in detail in following sections. The solid ceramic liner support tooling calculation supposes the use of an alumina liner. The second assembly supposes use of a ceramic-coated H-13 steel liner. In each case, however, a general method of liner-sleeve design has been developed which will permit design of supporting tooling for any liner material of known thermal expansion characteristic, modulus of elasticity, and adequate compressive and/or tensile strength.

All liners and supporting sleeves are shrink-fitted, to develop requisite balancing tangential and radial stresses throughout tooling areas highly stressed by extrusion pressure. Since the sleeves possess a relatively low thermal mass, it is important to be able to rapidly and accurately assemble the hot and cold parts. Otherwise, heat transfer may allow seizing of a heated sleeve on a cool sleeve before the heated sleeve is properly positioned.

This problem has been approached by design of a device for heating and rapid, accurate, placement of cold cylinders inside hot cylinders. Assembly drawings and an operating description of this equipment are presented in this report.

It is recognized that the liner-sleeve-container designs and sleeve assembly procedures detailed in the following sections are considerably more complex than those usually employed for extrusion tooling. The general procedure which is followed, though, is common to all container design calculations. Such calculations are based on a series of selective decisions as to liner and sleeve dimensions, materials, and interferences. Nominal thickness of liner and sleeves is decided first; shrink interference for development of desired stress follows.

In the present case, support requirements of the new classes of liner materials which will be employed in this study have placed demands on support tooling which cannot be met with conventional two-or-three-piece assemblies. The design which has been chosen attempts to exploit those mechanical properties of the liners which are high, without placing other demands which the material cannot meet. This, in turn, will permit use of a wider selection of liner materials. Such an advantage adequately compensates the effort of design and fabrication of the assemblies to be described.

II. LINER-SLEEVE-CONTAINER ASSEMBLY DESIGN

DESIGN 1: 1000-TON PRESS CONTAINER CALCULATION FOR A LINER HELD IN COMPRESSION UNDER ALL EXTRUSION CONDITIONS

A. Design Characteristics

Although the support tooling has been specifically designed to utilize ceramic materials for extrusion liner use, the ceramics themselves must possess certain properties, due to the stresses present in the extrusion operation. Since the liner must be held in compression under all extrusion conditions, it must have a compressive strength of at least 220,000 psi, to withstand shrink stresses generated by the support tooling. Once held in compression, the elastic modulus of the ceramic should be greater than that of the steel (over 30,000,000 psi) to avoid development of an excessive stress in the first supporting sleeve. The value of the thermal expansion coefficient of the liner may either be greater or less than that of the sleeves, but should not differ from the sleeve value by more than 50%. If the thermal expansion coefficient of the ceramic is much less than that of the sleeves, high stresses will develop in both liner and sleeves at room temperature, which, in turn, can cause the liner to fail in compression, and one or more of the sleeves to fail in tension. If the thermal expansion coefficient of the ceramic is much greater than that of the sleeves, liner will fall out of the first sleeve at room temperature.

Although the support tooling will not permit the liner to operate in tension, a small tensile strength in liner is required, if the ceramic is not to fail in shear during extrusion loading. Virtually all ceramic materials have a tensile strength of 6-10% of the compressive strength. This tensile property is adequate to prevent failure in the design employed.

A half-scale assembly drawing of the support tooling used to generate the desired compressive stress in the liner is shown in Figs. 1 and 2. It may be seen that five sleeves are used. The first four sleeves are successively shrink-fitted over the liner and one another. The fifth sleeve is shrink-fitted into the container. Assembly is designed to have a 0.0001-0.0005 in. clearance between fourth and fifth sleeve at its operating temperature of 600°F. This permits rapid removal of liner-and-4 sleeve assembly in event of liner failure. The flange on the fourth sleeve supports this assembly in position under no-load conditions. This flange is not intended to carry a high load during extrusion, however. An extrusion pressure of 5,650 psi will expand the outer radius of the fourth sleeve 0.0005 in., causing it to lock against container sleeve inner wall. This helps to reduce shear stress on fourth sleeve flange.

It may also be seen that the first three sleeves have 1/4 in. thick walls, while the fourth sleeve has a 1/2 in. wall. The increase in compressive stress obtained by use of thin-wall cylinders decreases as the radial distance from the container axis increases. Use of two shrink-fitted 1/4 in. wall sleeves in place of the 1/2 in. wall sleeve would do little to increase the compressive stress on the liner. Therefore, a 1/2 in. sleeve is used in this section of the assembly.

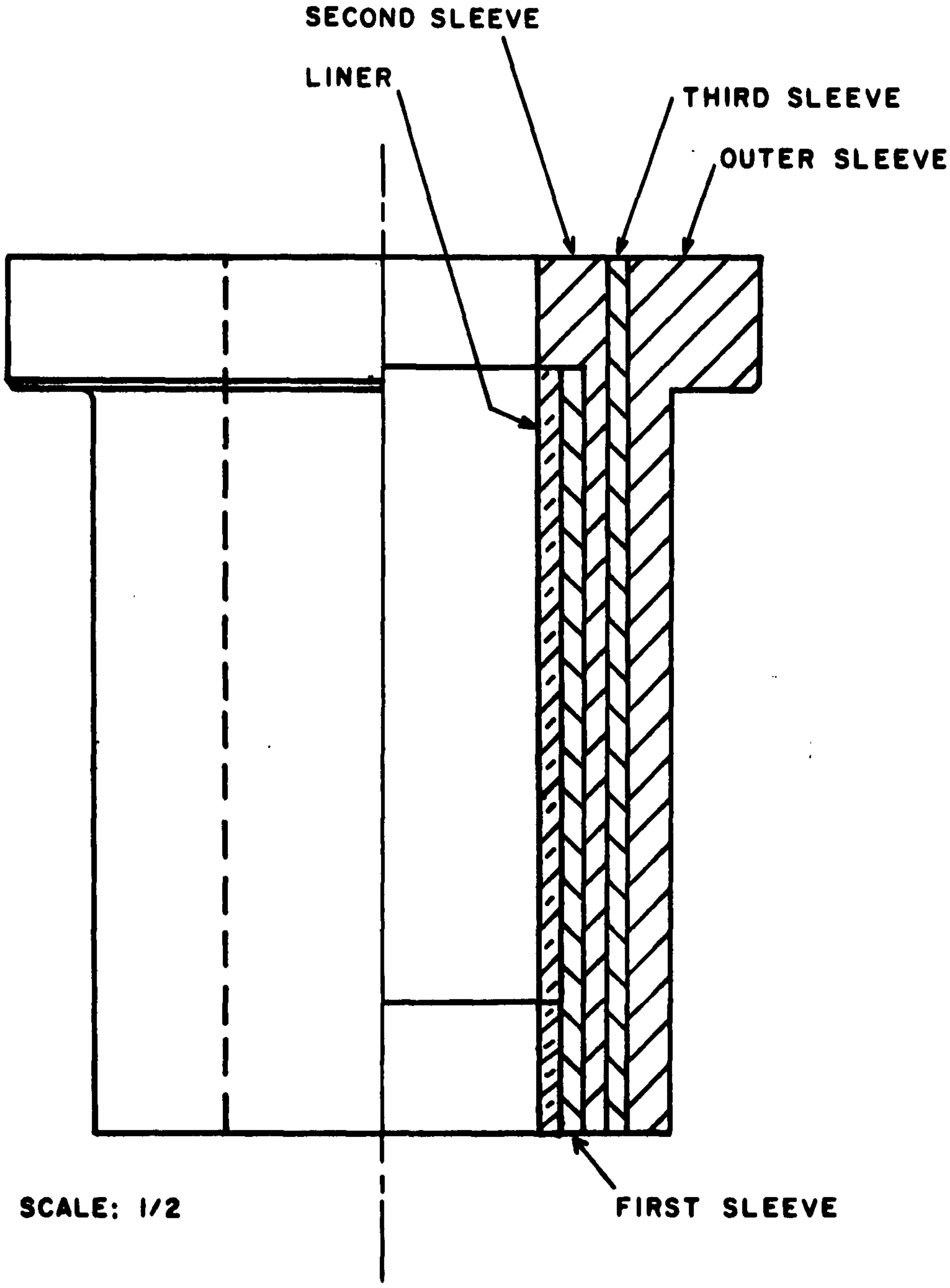


FIG. 1 LINER AND 4-SLEEVE ASSEMBLY

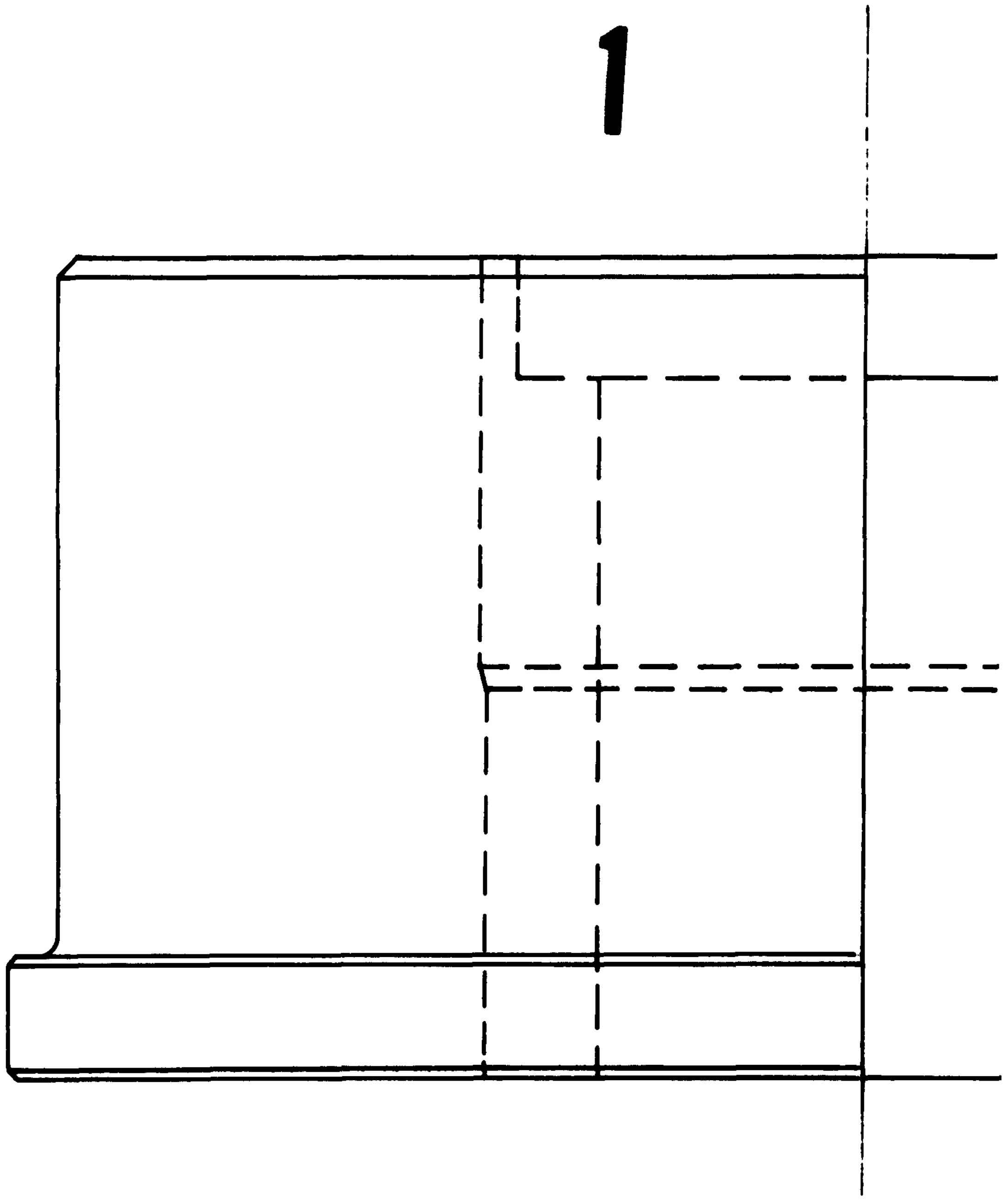
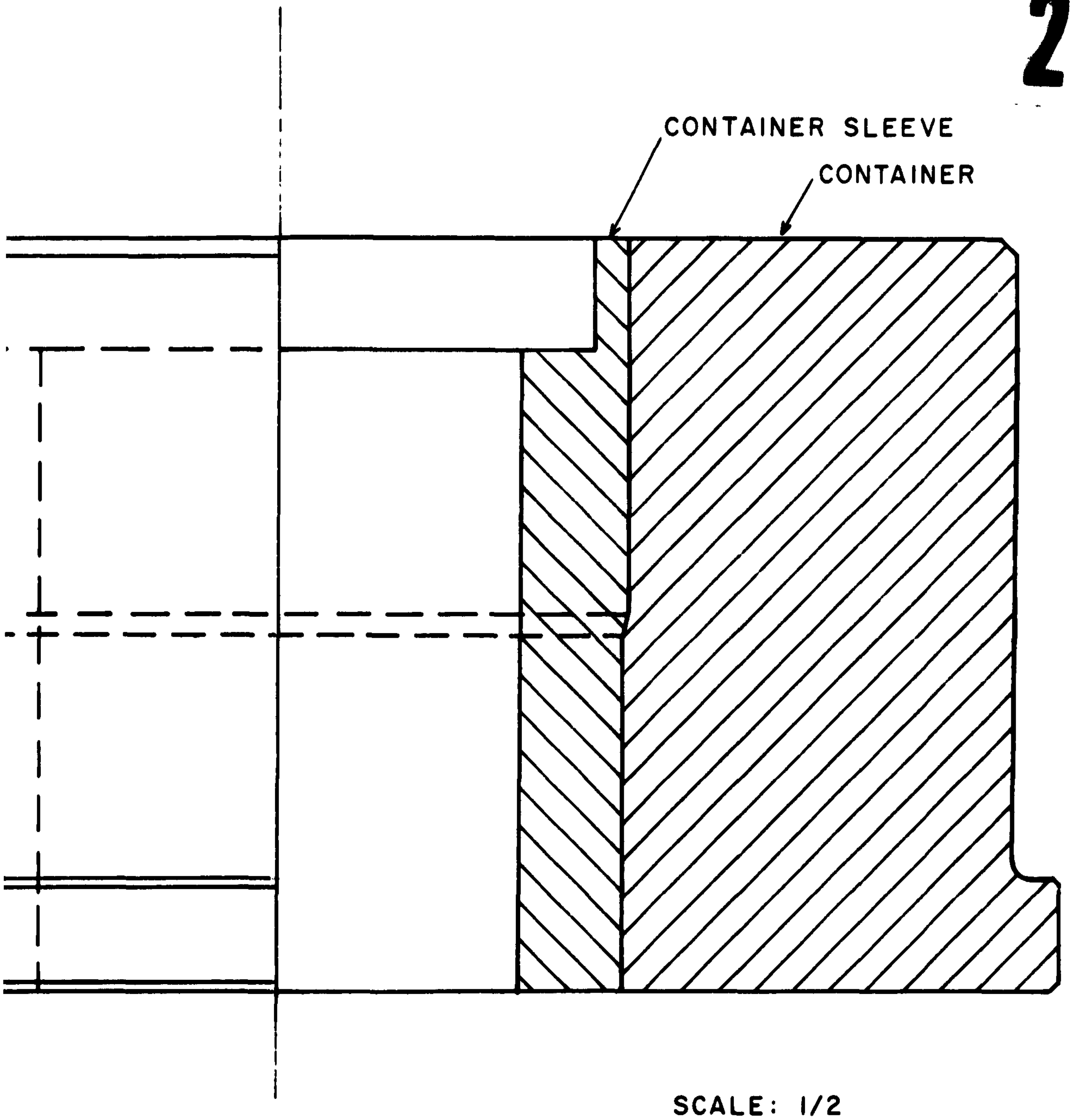


FIG. 2 CONTAINER SLEEVE



CONTAINER SLEEVE AND CONTAINER

Since the assembly shown in Fig. 1 places a high compressive stress on the liner, a significant liner axial tensile stress would be expected, even if coefficient of friction between liner and first sleeve is high. Consequently, it appeared desirable to incorporate a means for reduction of this axial tensile stress in the liner. This has been accomplished by use of a separate liner base support and a cantilevered section of the second sleeve. This design subjects the liner to an axial compressive stress when the second sleeve is placed in tension by shrink fitting. The parting line between liner and liner support base is covered by the extrusion die. The liner support base is made of the same material as liner to avoid generation of a stress differential in the first sleeve by any difference in thermal expansion coefficient or elastic modulus value existing between liner and liner support base.

The high compressive stress in the liner developed by the supporting sleeves demands use of a sleeve material which has a high tensile strength. In general, the tensile strength requirement of sleeves decreases as radial distance from container axis increases. Hence, outer sleeve and container may be made of material of lower tensile strength than that of the inner sleeves. In this particular design, all liner sleeves are Allegheny-Ludlum HTB-2 steel. Container sleeve is H-13 tool steel. Pertinent mechanical and physical properties of the two steels are given in Table I. To assure that all tooling operated below the proof stress, and preferably below the proportional limit, design tensile stresses were kept below 75% of the 0.2% offset yield strength at operating temperature under an extrusion pressure overload of at least 15%. This was achieved by designing the system for operation at 207,000 psi extrusion pressure, 15% above the actual peak working pressure of 180,000 psi.

Peak permissible loading has not been determined by restriction of tensile stresses to 75% of the 0.2% offset yield strength only, since it is possible for tooling to fail in shear under some conditions, without exceeding the permissible tensile load.

TABLE I

SELECTED MECHANICAL AND PHYSICAL PROPERTIES OF HTB-2 AND H-13 STEEL

Property	HTB-2	HTB-13
Young's Modulus: Room Temperature	29.3×10^6 psi	--*
600°F	25.3×10^6 psi	25.2×10^6 psi
800°F	23.8×10^6 psi	26.2×10^6 psi
Liner thermal expansion coefficient		
0-600°F	6.66×10^{-6}/°F	6.8×10^{-6}/°F
0-800°F	7.08×10^{-6}/°F	7.2×10^{-6}/°F
0-1000°F	7.22×10^{-6}/°F	7.4×10^{-6}/°F
0.2% offset tensile yield strength at 600°F when hardened and tempered at 1025°F	300,000 psi	--
0.2% offset tensile yield strength at 600°F at R_c 53-55	--	240,000 psi
0.2% offset tensile yield strength at 800°F at R_c 53-55	--	240,000 psi
0.2% offset tensile yield strength at 600°F at R_c	--	220,000 psi
0.2% offset tensile yield strength at 800°F at R_c 50-52	--	220,000 psi

* Blanks indicate that property is not pertinent to design.

Instead, tooling has been designed to limit octahedral shear stress to

$$T = 0.707\, S_o \; 1 - \frac{S_1 + S_2 + S_3}{3S_o} = T_o \; 1 - \frac{S_1 + S_2 + S_3}{3S_o} \text{ if } T_o = 0.707\, S_o,$$

where S_1, S_2, S_3 are the principal stresses, S_o the peak allowable tensile stress, and T the octahedral shear stress. This relation, developed by R. G. Sturm, has been successfully used in design of extrusion container assemblies on the Air Force heavy press program.*

Assumptions must also be made in regard to axial stress and strain behavior, to enable calculation of these quantities. In accordance with most recent container design practice used on the U. S. Air Force heavy press program, axial strain due to shrink stress has been taken as zero for areas where high shrink stresses are present. Axial stress is taken as zero where low shrink stresses are present. In the present design, axial strain has been assumed to be zero for the liner and first four sleeves. Axial stress has been assumed zero for container sleeve and container.

An operating temperature of 600°F for liner and supporting tooling appears to be preferable to 800°F for two reasons. First, the supporting steel sleeves are 15% stronger at 600°F than at 800°F. Secondly, sleeve design for operation at 800°F would place high compressive stresses on the liner and high tensile stresses on the sleeves, at room temperature, if thermal expansion coefficient of ceramic liner were appreciably less than that of the supporting steel sleeves. Since most ceramics have a considerably lower thermal expansion coefficient than steel, this is a likely effect. Design for 600°F operation results in a lower stress level in container and sleeves at room temperature. Or, alternately, liner materials possessing lower thermal expansion coefficients may be used in a 600°F design which could not be used in an 800°F design.

Assembly of shrink-fitted cylinders requires sufficient clearance between hot and cold pieces, and a means of rapidly and accurately inserting the cold cylinder inside the hot cylinder. Otherwise, premature

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* Kaiser Aluminum and Chemical Corp. and Sturm and O'Brien, "Failure Analysis, Modification, and Redesign of Containers for the Loewy 8100-Ton Extrusion Presses," Final Report, March 31, 1958, Book II Sponsored by U. S. A. F. Contract AF 33(600)-34645.

seizure may result, when an assembly attempt is made. Three procedures have been employed to facilitate this assembly. First, shrink fits have been designed to make refrigeration of cold sleeves unnecessary. Cold sleeves will be at room temperature; hot sleeves will be at 1025°F. (This upper temperature limit is fixed by the tempering temperature of the steel used.) Secondly, a minimum clearance of 0.002 in/in of sleeve radius has been maintained, up to a maximum of 0.006 in. Finally, a heating and transfer system has been designed which heats the outer sleeve, then rapidly and accurately transfers the cold sleeve into the hot sleeve.

B. Liner and Sleeve Machining and Shrink-Fitting Data

In practice, sleeve liner diameters will be precision machined before shrink fitting. Outer diameters will be rough machined, with grinding stock allowed. After shrink fitting, outer diameters will be ground to size. Machining data are given in Table II. Unstressed outer diameters have been increased by 0.0120 in. over calculated size to allow grinding stock for finishing. Machining tolerance is $\pm$ 0.0004 in., except as noted.

Machining dimensions have been calculated for a temperature of 75°F. Since liner and sleeves have different thermal expansion coefficients, machining at a different ambient temperature will develop a different shrink stress in sleeves when they are fitted. Hence, machining temperature should be held as close to 75°F as practicable.

Shrink fit temperature for all sleeves is 1025°F. A room temperature of 75°F is assumed in calculating shrink fits. Sleeve clearances at assembly temperatures are sufficiently high to permit a $\pm$ 10°F change in room temperature without significantly increasing difficulty of assembly.

Stresses throughout liner, sleeves, and container due to shrink fitting, and extrusion, are shown in Figure 9, Appendix, as a function of radial distance from liner axis.

Procedures for calculation of all plotted stresses and tabulated machining dimensions are given in the Appendix, under "Design 1."

TABLE II

MACHINING DIAMETERS OF LINER AND SLEEVES FOR FOUR-SLEEVE ASSEMBLY

Part	Inner Diameter, in.	Outer Diameter, in.	Final Size of Stressed Outer Diameter, in.
Liner	3. 6000	4. 1250*	---
1st Sleeve	4. 1098	4. 6218**	4. 6228
2nd Sleeve	4. 6012	5. 1332**	5. 1384
3rd Sleeve	5. 1132	5. 6452**	5. 6542
4th Sleeve	5. 6274	6. 6322**	6. 6202

* Grinding tolerance of $\pm$ 0. 001 in. for ceramics

** Tolerance of $\pm$ 0. 002 in.

DESIGN 2: 1000-TON PRESS CONTAINER CALCULATION FOR A LINER WITH BALANCED TENSION AND COMPRESSION STRESS AT 0.5 OF MAXIMUM EXTRUSION PRESSURE

A. Design Characteristics

This assembly has been designed to make use of ceramic-coated metal liners and elevated temperature metal liners. Ceramic coatings generally have modest elastic strain capability; elevated temperature metals possess a relatively low yield strength in both tension and compression. Support tooling design for such materials should be such that minimal demands are made of the liner for elastic strain, tensile,and compressive strength. This has been accomplished by design of a sleeve assembly which places the liner under a tangential compressive stress equal to one-half of the peak tangential stress developed during extrusion. This reduces peak tensile stress on the liner to one-half the stress generated by the peak extrusion pressure.

In this particular case, tooling has been designed for an extrusion pressure of 210,000 psi, 16.7% above the peak operating pressure of 180,000 psi. The 210,000 psi extrusion pressure generates a 224,000 psi peak tangential stress in the liner. A -112,000 psi tangential compressive stress is placed on the liner wall, to cause liner to operate between -112,000 and +112,000 psi. Tangential elastic strain of liner wall will then range between -0.38% and +0.38%. Accordingly, peak tensile and compressive operating stress requirement of a liner is $\pm$ 112,000 psi, and peak elastic strain capability of a coating becomes $\pm$0.38%.

This design supposes the use of liner materials whose thermal expansion and elastic modulus coefficients are within $\pm$ 10% of that of the supporting steel sleeves. This permits use of several materials which appear to have requisite mechanical properties at 1200°F. Ceramic coatings must, of course, have thermal expansion coefficients which are compatible with the base material. Considerable information is available on compatible H-13 steel coatings. Since this tool steel has suitable properties for liner use, it has been selected as the base material for coating application.

A half-scale assembly drawing of the support tooling used to generate the desired compressive stress in the liner is shown in Fig. 3. It may be seen that this assembly has three shrink-fitted sleeves, in contrast to the four-sleeve assembly shown in Fig. 1. Since less compressive stress is required on a metal liner than on a ceramic liner, three sleeves are sufficient for the purpose. Container sleeve and container design are the same as used in Design 1, and are shown in Fig. 2. Clearance between the third sleeve and container sleeve is maintained at 0.0001-0.0005 in., at operating temperature of 800°F. This permits rapid removal of liner and three-sleeve assembly in event of liner failure.

Since compressive stress on liner is moderate, a sleeve material may be used which possesses lower tensile properties than the HTB-2 steel. A H-13 tool steel appears well suited for this application. Pertinent mechanical and physical properties of this steel are given in Table I. As in Design 1, design tensile stresses have been kept below 75% of the 0.2% offset yield strength, at operating temperature, under a 15% extrusion pressure overload; and octahedral shear stress has been limited to values calculated by the Sturm criterion. Similar assumptions to those in Design 1 have been made concerning axial stress and strain behavior.

Although Design 2 has been carried out for an operating temperature of 800°F, tooling may be used at 600°F, if desired. Since thermal expansion and elastic modulus coefficients of liner are similar to those of supporting sleeves, operation at 600°F carries no advantage over operation at 800°F, other than presenting an ability to run comparative behavior studies on the two designs when it appears desirable. If thermal conductivity of the ceramic coating or elevated temperature liner material is high, it may be desirable to operate tooling at 800°F to minimize billet surface chilling.

Similar clearances are maintained between hot and cold cylinders to be shrink-fitted in both Design 1 and Design 2. Since less compressive stress is generated in Design 2 by shrink fitting, sleeves need not be heated to as high a temperature. In this case, cold sleeves will be at room temperature; hot sleeves will be below 850°F. This relatively low upper temperature limit makes it possible to use sleeves which are hardened to R_c53-55. This

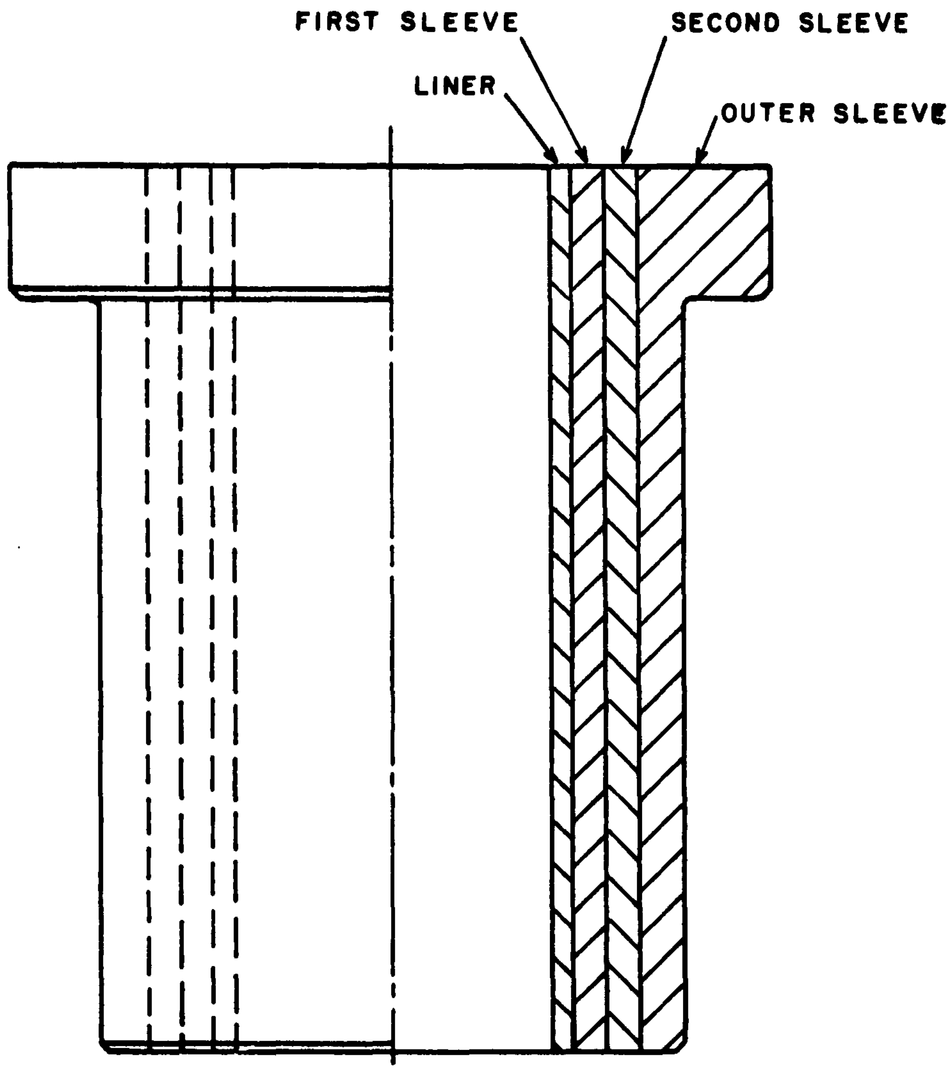

FIG. 3 CERAMIC COATED METAL AND ELEVATED TEMPERATURE METAL LINER-SLEEVE ASSEMBLY.

hardness has a sufficiently high accompanying tensile strength to permit employment of the same degree of design conservatism in Design 2 that is present in Design 1, even though only three supporting sleeves are used.

B. Liner and Sleeve Machining and Shrink-Fitting Data

In practice, sleeve inner diameters will be precision machined before shrink fitting. Outer diameters will be rough machined, with grinding stock allowed. After shrink fitting, outer diameters will be ground to size. Machining and shrink fitting data are given in Table III. Unstressed outer diameters have been increased by 0.0120 in. over calculated size to allow grinding stock for finishing. Machining tolerance is ± 0.0004 in., except as noted.

Ambient temperature is of no importance in machining operations, but it must remain reasonably constant. For example, a 10°F change in temperature will cause the outer diameter of the third sleeve to change by 0.00048 in. This is over half the tolerance allowed. Temperature change effects are not as pronounced on the smaller diameter sleeves.

A room temperature of 75°F is assumed in calculating shrink-fit temperature. Sleeve clearances at assembly temperatures are sufficiently high to permit a ± 20°F change in room temperature without significantly increasing difficulty of assembly.

Stresses throughout liner, sleeves, and container due to shrink fitting and extrusion are shown in Figure 13, Appendix, as a function of radial distance from liner axis.

Procedures for calculation of all plotted stresses and tabulated machining dimensions are given in the Appendix, under "Design 2." Section 13 in the Appendix shows that liner inner diameter will contract 0.0156 in. due to shrink stress. This contraction, and thickness of any coating placed on liner wall, must be considered in establishing die diameter, since dies fit inside liner.

TABLE III

MACHINING DIAMETERS AND SHRINK FIT TEMPERATURE OF LINER AND SLEEVES FOR THREE-SLEEVE ASSEMBLY

Part	Inner Diameter, in.	Outer Diameter, in.	Final Size of Stressed Outer Diameter, in.	Shrink Fit Temperature, °F
Liner	3.6000	4.1300	---	---
1st Sleeve	4.1172	4.8898*	4.8800	845
2nd Sleeve	4.8690	5.6294*	5.6200	730
3rd Sleeve	5.6030	6.6278*	6.6197	795

* Machining tolerance is $\pm$ 0.002 in.

III. SLEEVE HEATING AND TRANSFER DEVICE FOR ASSEMBLY OF COMPOUND SLEEVES

A. General Description of Operation

The sleeve to be heated is placed over a Monel metal block containing cartridge heaters rated at 6 kilowatts. The sleeve to be inserted in the heated sleeve is held in a jig well above the Monel block. The heater block heats the surrounding sleeve to the desired temperature. The block is then dropped out of the sleeve. Next, the sleeve to be inserted is dropped into the heated sleeve, occupying the space formerly taken by the heating block.

An assembly drawing of this device is shown in Figure 4. Numbers in parentheses in the following section refer to parts on this drawing.

B. Shrink Fitting Procedure

1. Adjustment of Centering Device for Heated Sleeve

The two halves of the Oven Wall (19) are first removed from the Insulator Plate (3) by lifting off. The Centering Angles (7) are adjusted to their inner position by loosening the Centering Clamps (9) and sliding the Centering Angles in towards the center. Then, the four Centering Blocks (5) are dropped behind them. The Centering Angles are then held back against the Centering Blocks and clamped in position by the Centering Clamps (9).

2. Positioning of Liner

The Liner is next clamped between the Adapter Plate (28) and the Bottom Plate (30) by the Bolt (31). The Adapter Plate (28) is then clamped to the Rod Plate (27) by three Clamps (29). Air pressure on the Liner Lift Cylinder (25) then holds the Liner up and out of the way.

3. Positioning and Heating of Sleeve

The sleeve is now centered by setting it on the steps on the Centering Angles (7). The Centering Blocks (5) are calibrated to allow for diametral expansion of the sleeve on heating, and will bring the hot sleeve to center. The two Oven Walls (19) are next set back in place on the Insulating Plate (3). The Oven Cover (22) is next set in place. Air pressure, through

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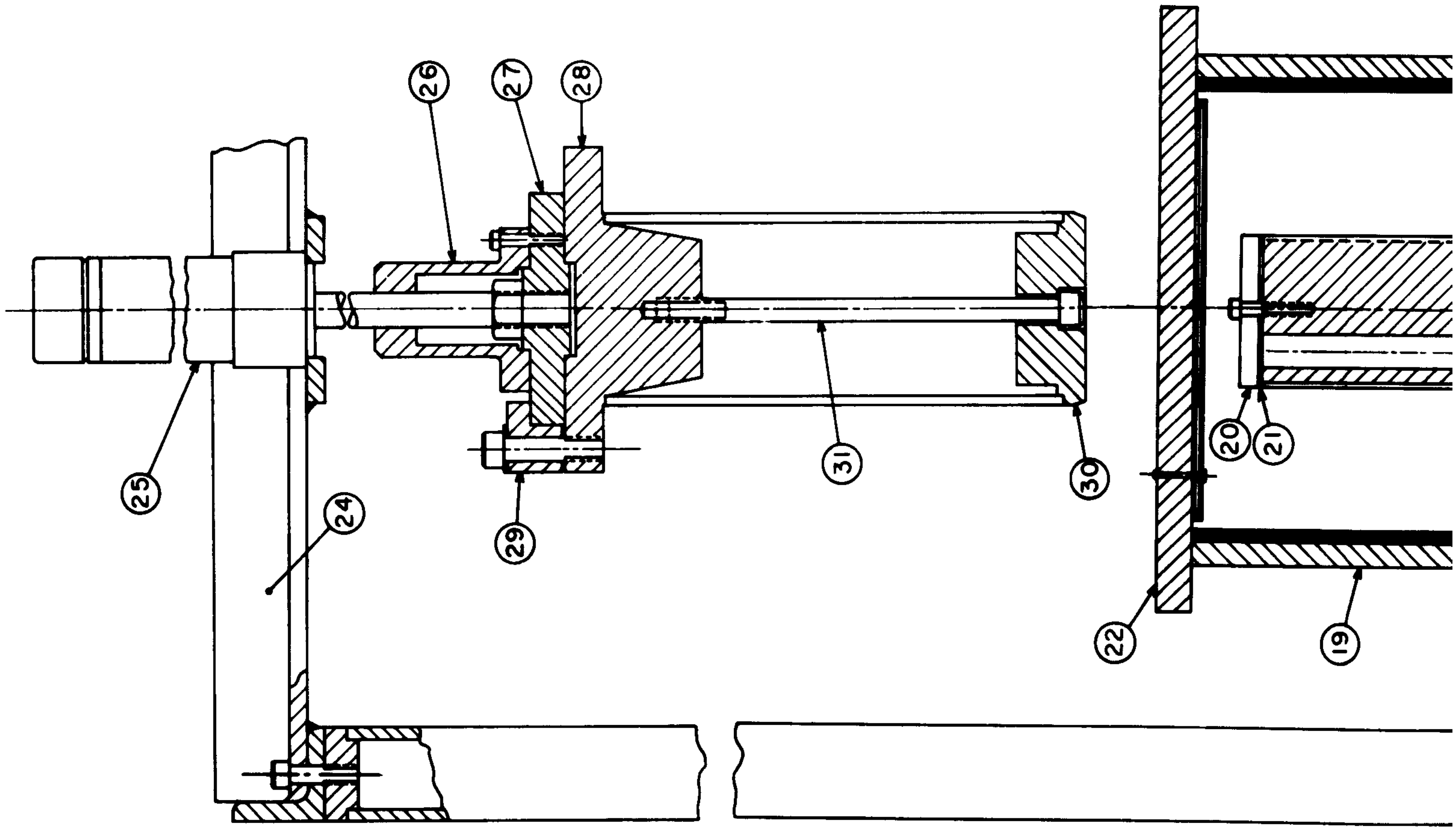

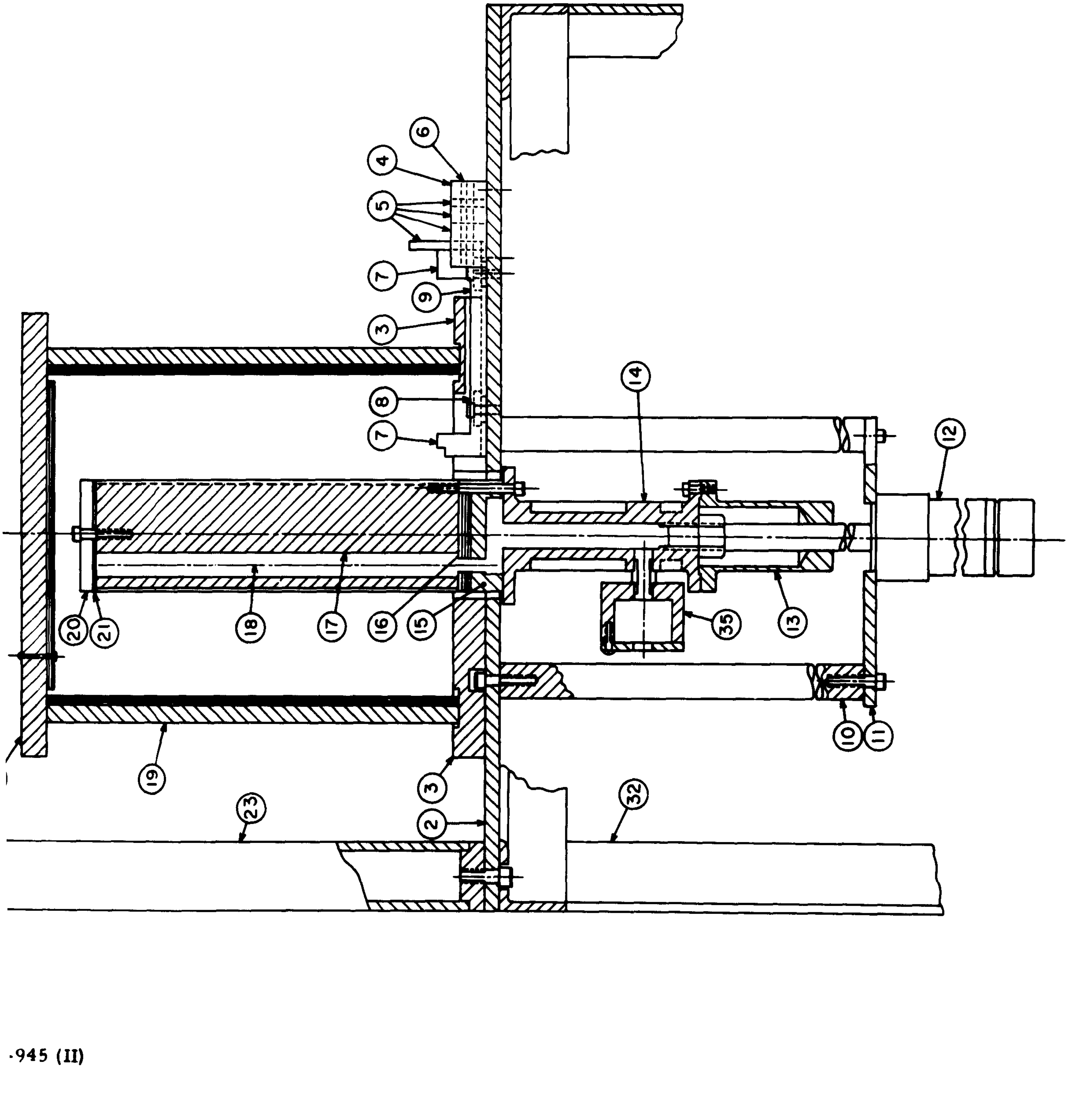

FIG. 4 SHRINK FIT ASSEMBLY DEVICE

the proper control valve, now raises the R-Monel, 6000 watt Heater Body (17) into the oven to bring the sleeve up to temperature.

4. Removal of Heating Block and Transfer of Liner

When the sleeve is at desired temperature, the Oven Cover (22) is lifted off. The proper control valve switches air to the top of the Heater Lift Cylinder (12) lowering the Heater Body (17) out of the sleeve. The air valve controlling the Liner Lift Cylinder (25) is actuated to plunge the liner down into the hot sleeve, and holds the assembled sleeve and liner until cooling has shrunk them together.

A step on the Adapter Plate (28) allows the liner to enter the hot sleeve a distance equal to one-half the linear expansion of the hot sleeve.

5. Removal of Liner-Sleeve Assembly

When the liner and sleeve have shrunk together, the Liner Lift Cylinder (25) lifts the assembled liner and sleeve up above the Oven.

6. Readjustment of Centering Device for Next Heated Sleeve

The Centering Clamps (9) are now loosened, the first Centering Block (5) is lifted up from behind the Centering Angles (7), and the Angles are moved back against the second Centering Block. This accommodates the Centering Angles (7) to the next size sleeve to be shrunk on the first assembly.

IV. FUTURE WORK

Work designated Phase II, "Performance Testing of New Liners," will commence as soon as approval of this Phase I report is secured from the Procuring Contract Officer.

Respectfully submitted,

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APPENDIX

DESIGN 1: 1000-TON PRESS CONTAINER CALCULATION FOR A LINER HELD IN COMPRESSION UNDER ALL EXTRUSION CONDITIONS

A. General Procedure for Container Design Calculations

The design calculation is divided into a number of objectives, and steps for achieving the specific objectives. Objectives are designated by numbers, related sequential steps by lower case letters. All equations and their solutions are written in the order used in the calculation. Graphs of liner, sleeve, and container stress as a function of radial position are plotted for three conditions:

(1) Stress due to shrink fitting

(2) Stress due to a 207,000-210,000 psi extrusion pressure

(3) Stress due to combined effect of shrink fitting and 210,000 psi extrusion pressure.

Since any given stress, interfacial pressure, or displacement may be a function of as many as ten variables, and many such functions must be calculated, designation of a particular function by a single symbol becomes impractical. Instead, a notation has been devised to describe the type of the variable, its location, and factors which produce it. The system used may be described as follows:

(1) Stresses

Stresses are identified by the letter S followed by a series of subscripts. The first subscript, or group of subscripts, describes the location of the stress. This is followed by a letter T or R indicating whether the stress is tangential or radial. Additional numerals or letters describe the factors causing the stress. As examples, S_{LR1} indicates a stress throughout the liner which is radial, and generated by the first sleeve. $S_{(1,2,3)T4}$ would be a tangential stress throughout the first three sleeves, generated by the fourth sleeve. $S_{(L,1,2,3,4)\ R(e2)}$ is a radial stress acting through the liner and four sleeves caused by stem pressure P_{e2}.

(2) Pressures

Interfacial pressures(not stem pressures) are identified by the letter P followed by subscripts. The first subscript group before a comma identifies the location of the pressure. Following subscripts denote the cause of the pressure. As examples, $P_{A, e2}$ indicates a pressure acting at a radial distance A from the container centerline, which is generated by stem pressure P_{e2}. $P_{L1, 4}$ indicates a pressure acting at the interface between the liner and the first sleeve, generated by the fourth sleeve.

(3) Radial Displacements

Radial displacements are identified by the letter U followed by subscripts. The first character indicates the liner, or sleeve number involved. The second letter indicates the location of the displacement, and numbers following a comma indicate the cause of the displacement, As examples, $U_{4F, 4}$ indicates a displacement of the fourth sleeve at a radial distance F from the container centerline, generated by the fourth sleeve. $U_{LB, e2}$ indicates a displacement of the liner at distance B, generated by extrusion pressure P_{e2}. $U_{(1, 2, 3, 4)F, e2}$ indicates a displacement of first-second-third-fourth combination sleeve assembly at a distance F due to extrusion pressure P_{e2}.

This notation system is also useful for describing elastic moduli and linear thermal expansion coefficients. In these cases, notation is simplified, because only two different materials are used at three different temperatures. Elastic moduli are identified by the letter Y, thermal expansion coefficient by α. Subscripts indicate operating temperature, and whether material is a ceramic liner type or a steel. Examples of subscript application are Y_{S600}, indicating an elastic modulus of steel at 600°F; Y_{L75}, elastic modulus of a liner at 75°F; or α_{S800}, thermal expansion coefficient of steel at 800°F.

B. Specific Procedure

1. Liner-First Sleeve Interference at 600°F and Dimension of First Sleeve Inner Radius at 75°F

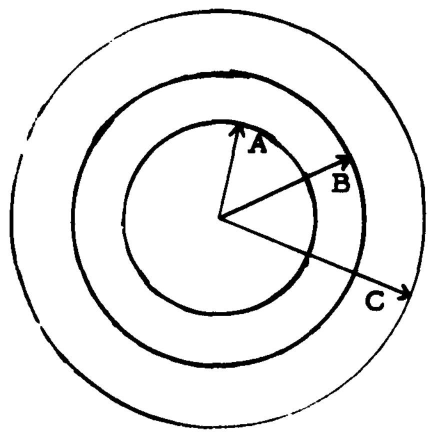


FIG. 5 - LINER AND FIRST SLEEVE ASSEMBLY

t	=	temperature, °F
A	=	liner inner radius = 1.804 in., nominal
B	=	liner outer radius and 1st sleeve inner radius = 2.065 in., nominal
C	=	1st sleeve outer radius = 2.315 in., nominal
Y_{L600}	=	47.7×10^6 psi
Y_{S600}	=	25.3×10^6 psi
α_{L600}	=	3.98×10^{-6}/°F
α_{S600}	=	6.66×10^{-6}/°F
α_{S1000}	=	7.22×10^{-6}/°F

a. Determine unstressed dimensions of liner outer radius and 1st sleeve inner radius at 600°F, to obtain interference at 600°F

Liner outer radius is

$$B_{L600} = B_{L75}\,(1 + \alpha_{L600}\,\Delta t_{600-75})$$

$$B_{L600} = 2.9693 \text{ in.}$$

First sleeve inner radius is

$$B_{1S600} = B_{75}\,(1 + \alpha_{S600}\,\Delta t_{600-75})$$

$$= \frac{B_{1025}(1 + \alpha_{600}\,\Delta t_{600-75})}{1 + \alpha_{S1000}\,\Delta t_{1025-75}}$$

$$B_{1S600} = 2.0612 \text{ in.}$$

Difference in unstressed liner outer radius and unstressed 1st sleeve inner radius at 600°F is

$$\beta_{L1} = 2.0693 - 2.0612 = 0.0081 \text{ in.}$$

b. Determine unstressed 1st sleeve inner radius at 75°F, to obtain machining dimension

$$B_{75} = \frac{B_{1025}}{1 + \alpha_{1000}\Delta t_{1025-75}} = 2.0549 \text{ in.}$$

Machined size of 1st sleeve inner radius, at 75°F, is 2.0549 in.

2. <u>Stress on Liner and First Sleeve Due to Liner-First Sleeve Shrink Fit, at 600°F</u>

a. Determine deformation of liner outer radius and 1st sleeve inner radius due to 1st sleeve shrink, in terms of liner-1st sleeve interfacial pressure

Deformation of liner outer radius due to 1st sleeve shrink is

$$U_{LB,1} = -\left[\frac{BP_{L1}}{Y_{L600}}\right]\left[\frac{A^2 + B^2}{B^2 - A^2} - \mu\right] = -3.11 \times 10^{-7}\,P_{L1}$$

$$\mu = \text{Poisson's ratio} = 0.3$$

Deformation of 1st sleeve inner radius due to 1st sleeve shrink is

$$U_{1B,1} = \left[\frac{BP_{L1}}{Y_{S600}}\right]\left[\frac{B^2 + C^2}{C^2 - B^2} + \mu\right] = 7.13 \times 10^{-7} P_{L1}$$

b. Set the two deformations equal to each other and solve for interfacial pressure.

$$U_{LB,1} + U_{1B,1} = \beta_{L1} \quad \text{(absolute value sum)}$$

$$8.1 \times 10^{-3} = 10.3 \times 10^{-7} P_{L1}$$

$$P_{L1,1} = 7.91 \times 10^{-3} \text{ psi}$$

Interfacial pressure between liner and 1st sleeve is 7,910 psi.

c. Determine tangential and radial stress in liner.

$$S_{LT,1} = -\frac{P_{L1}B^2}{B^2 - A^2}\left[1 + \frac{A^2}{r^2}\right] = -33,600 - \frac{112,000}{r^2}$$

At $r = A$, $S_{LT} = -67,200$ psi.

Radial compressive stress on liner is

$$S_{LR,1} = -33,600 + \frac{112,000}{r^2}$$

At $r = A$, $S_{LR} = 0$.

d. Determine tangential and radial stress in 1st sleeve.

$$S_{1T,1} = \frac{P_{L1}B^2}{C^2 - B^2}\left[1 + \frac{C^2}{r^2}\right] = 29,400 + \frac{158,000}{r^2}$$

$$S_{1R,1} = 29,400 - \frac{158,000}{r^2}$$

3. <u>Stressed First Sleeve Outer Radius, at 75°F</u>

a. Determine interference between unstressed liner outer radius and 1st sleeve inner radius.

At 75°F, liner outer radius is 2.0650 in., and 1st sleeve inner radius is 2.0459 in.

$$\gamma_{L1} = 2.0650 - 2.0549 = 0.0101 \text{ in.}$$

b. Determine deformation of liner outer radius due to 1st sleeve shrink, in terms of interfacial pressure between liner and 1st sleeve.

Using results of 2a, deformation of liner outer radius due to 1st sleeve shrink is

$$U_{LB,1} = -3.11 \times 10^{-7} P_{L1} \left[\frac{Y_{L600}}{Y_{L75}} \right] = -3.08 \times 10^{-7} P_{L1}$$

where $Y_{L75} = 4.80 \times 10^{7}$ psi.

c. Determine deformation of 1st sleeve inner radius due to 1st sleeve expansion in terms of interfacial pressure between liner and 1st sleeve.

Using results of 2a, deformation of 1st sleeve inner radius, due to 1st sleeve expansion, is

$$U_{1B,1} = 7.13 \times 10^{-7} P_{L1} \left[\frac{Y_{S600}}{Y_{S75}} \right] = 6.15 \times 10^{-7} P_{L1}$$

d. Equate absolute value sum of deformation of liner and 1st sleeve to interference, and solve for interfacial pressure.

$$U_{LB,1} + U_{1B,1} = \beta_{L1,1}$$

$$P_{L1,1} = 11,000 \text{ psi}$$

e. Determine deformation and outer radius of stressed sleeve.

$$U_{1C,1} = \frac{2B^2 C P_{L1}}{Y_{S75}(C^2 - B^2)} = 0.0065 \text{ in.}$$

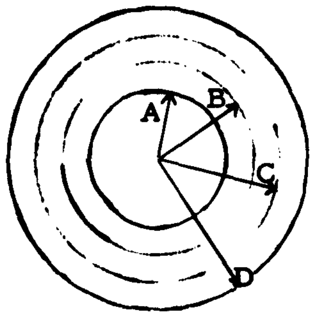
Outer radius of unstressed 1st sleeve is 2.3049 in.

Outer radius of stressed 1st sleeve, at 75°F, is 2.3114 in.

f. Determine tangential stress at liner inner radius, at 75°F

$$S_{LT,1} = \frac{2P_{L1}B^2}{B^2 - A^2} = -93,400 \text{ psi}$$

4. <u>Pressure Generated at Liner-First Sleeve Interface and First Sleeve-Second Sleeve Interface by Second Sleeve Shrink Fit, at 600°F</u>



D = 2.565 in., nominal

FIG. 6 - LINER, FIRST, AND SECOND SLEEVE ASSEMBLY

a. Determine 2nd sleeve inner radius at 1025°F which satisfies clearance requirement for 1st sleeve stressed outer radius at 75°F

First sleeve outer radius, at 75°F, is 2.3114 in. when shrunk over liner. When 2nd sleeve is heated to 1025°F, let there be a 0.0050 in. clearance between 1st and 2nd sleeve. Inner radius of 2nd sleeve is then 2.3164 in. at 1025°F

Unstressed inner radius of 2nd sleeve at 600°F is

$$C_{2S600} = \frac{C_{2S1025}(1 + \alpha_{S600}\,\Delta t_{600-75})}{1 + \alpha_{S1000}\,\Delta t_{1025-75}} = 2.3086 \text{ in.}$$

b. Determine expansion of 1st sleeve outer radius at 600°F from interfacial pressure found in 2b.

$$U_{1C,1} = \frac{2B^2CP_{L1,1}}{E_{S600}(C^2 - B^2)} = 0.0054 \text{ in.}$$

c. Determine unstressed outer radius of 1st sleeve at 600°F and add to value in 4b to obtain stressed 1st sleeve outer radius

Unstressed 1st sleeve outer radius at 600°F is

$$B_{1S600} = B_{1S75}(1 + \alpha_{S600}\Delta t_{600-75}) = 2.3130 \text{ in.}$$

Stressed 1st sleeve outer radius, at 600°F, is 2.3130 + 0.0054 = 2.3184 in.

d. Subtract 4c results from 4a result to obtain 1st-2nd sleeve interference at 600°F.

$$\beta_{12} = 2.3184 - 2.3086 = 0.0098 \text{ in.}$$

e. Determine unstressed 2nd sleeve inner radius at 75°F to obtain machining dimension

$$C_{2S75} = \frac{C_{2S1025}}{1 + \alpha_{S1000}\Delta t_{1025-75}} = 2.3006 \text{ in.}$$

Machining dimension of 2nd sleeve inner radius is 2.3006 in.

f. Determine displacement of liner at liner-1st sleeve interface in terms of interfacial pressure developed at this interface by 2nd sleeve, at 600°F

$$U_{LB,2} = -\frac{BP_{L1,2}}{Y_{L600}}\left[\frac{A^2 + B^2}{B^2 - A^2} - \mu\right] = -3.11 \times 10^{-7} P_{L1,2}$$

g. Determine displacement of 1st sleeve at liner-1st sleeve interface in terms of pressure exerted at liner-1st sleeve interface, and pressure exerted at 1st-2nd sleeve interface by 2nd sleeve, at 600°F

$$U_{1B,2} = -\left[\frac{1-\mu}{Y_{S600}}\right]\left[\frac{B^2P_{L1,2}-C^2P_{12,2}}{C^2-B^2}\right]B + \left[\frac{1+\mu}{Y_{S600}}\right]\left[\frac{B^2C^2(P_{L1,2}-P_{12,2})}{B(C^2-B^2)}\right]$$

$$U_{1B,2} = 7.12 \times 10^{-7}P_{L1,2} - 7.69 \times 10^{-7}P_{12,2}$$

h. **Equate expressions developed in 4f and 4g to obtain liner-1st sleeve interfacial pressure in terms of 1st-2nd sleeve interfacial pressure, at 600°F**

$$-3.11 \times 10^{-7}P_{L1,2} = 7.12 \times 10^{-7}P_{L1,2} - 7.69 \times 10^{-7}P_{12,2}$$

$$P_{L1,2} = 0.752P_{12,2}$$

i. **Determine displacement of 1st sleeve outer radius due to $P_{L1,2}$ and $P_{12,2}$**

$$U_{1C,2} = \frac{1-\mu}{Y_{S600}}\left[\frac{B^2P_{L1,2}-C^2P_{12,2}}{C^2-B^2}\right]C + \frac{1+\mu}{Y_{S600}}\left[\frac{B^2C^2(P_{L1,2}-P_{12,2})}{C^2-B^2)C}\right]$$

$$U_{1C,2} = 7.03 \times 10^{-7}\ P_{L1,2} - 7.67 \times 10^{-7}P_{L2,2}$$

j. **Substitute result of 4h in 4i to express displacement of 1st sleeve outer radius as a function of $P_{12,2}$ only**

$$U_{1C,2} = -2.39 \times 10^{-7}P_{12,2}$$

k. **Determine displacement of inner radius of 2nd sleeve due to $P_{12,2}$**

$$U_{2C,2} = \frac{CP_{12,2}}{Y_{S600}}\left[\frac{C^2+D^2}{D^2-C^2} + \mu\right] = 9.84 \times 10^{-7}P_{12,2}$$

l. Add absolute value of 4j and 4k and equate to 4d. Solve for $P_{12,2}$

$$(2.39 + 9.84)\ 10^{-7}\ P_{12,2} = 0.0098$$

$$P_{12,2} = 8,010 \text{ psi}$$

m. Substitute 4l in 4h to obtain $P_{L1,2}$

$$P_{L1,2} = 6,020 \text{ psi}$$

5. <u>Stress Generated in Liner, First, and Second Sleeve Due to First-Second Sleeve Shrink Fit, at 600°F</u>

a. Determine tangential and radial stress in liner

$$S_{LT2} = -\frac{P_{L1,2}B^2}{B^2 - A^2}\left[1 + \frac{A^2}{r^2}\right] = -25,500 - \frac{82,700}{r^2}$$

$$S_{LR2} = -25,500 + \frac{82,700}{r^2}$$

At $r = A$, $S_{LR2} = 0$

b. Determine tangential and radial stress in 1st sleeve

$$S_{1T2} = -\frac{B^2P_{L1,2} - C^2P_{12,2}}{C^2 - B^2} + \frac{(P_{L1,2} - P_{12,2})\ B^2C^2}{r^2\ (C^2 - B^2)}$$

$$S_{1T2} = -15,400 - \frac{39,800}{r^2}$$

$$S_{1R2} = -15,400 + \frac{39,800}{r^2}$$

c. Determine tangential and radial stress in 2nd sleeve

$$S_{2T2} = \frac{C^2P_{12,2}}{D^2 - C^2}\left[1 + \frac{D^2}{r^2}\right] = 37,000 + \frac{242,000}{r^2}$$

$$S_{2R2} = 37,000 - \frac{242,000}{r^2}$$

6. **Outer Radius of Stressed Second Sleeve Due to First-Second Sleeve Shrink Fit, at 75°F**

a. Determine interference between stressed 1st sleeve outer radius and unstressed 2nd sleeve inner radius at 75°F, by use of values in 3 e and 4e

$$Y_{12} = 2.3114 - 2.3006 = 0.0108 \text{ in.}$$

b. Determine displacement of liner at liner-1st sleeve interface in terms of interfacial pressure developed at this interface by 2nd sleeve, at 75°F, from results of 4f

$$U_{LB,2} = -3.11 \times 10^{-7} P_{L1,2} \left[\frac{Y_{L600}}{Y_{L75}}\right] = -3.09 \times 10^{-7} P_{L1,2}$$

c. Determine displacement of 1st sleeve at liner-1st sleeve interface in terms of pressure exerted at liner-1st sleeve interface, and pressure exerted at 1st-2nd sleeve interface by 2nd sleeve, at 75°F, from 4g

$$U_{1B,2} = (7.12 P_{L1,2} - 7.69 P_{L2,2})\, 10^{-7} \left[\frac{Y_{S600}}{Y_{S75}}\right]$$

$$U_{1B,2} = (6.15 P_{L1,2} - 6.64 P_{L2,2})\, 10^{-7}$$

d. Equate expressions developed in 6b and 6c to obtain liner-1st sleeve interfacial pressure in terms of 1st-2nd sleeve interfacial pressure, at 75°F

$$-3.09 \times 10^{-7} P_{L1,2} = 6.15 \times 10^{-7} P_{L1,2} - 6.64 \times 10^{-7} P_{L2,2}$$

$$P_{L1,2} = 0.718 P_{L2,2}$$

e. Determine displacement of 1st sleeve outer radius due to $P_{L1,2}$ and $P_{12,2}$ at 75°F, from 4i

$$U_{1C,2} = (7.03 P_{L1,2} - 7.67 P_{L2,2})\, 10^{-7} \left[\frac{Y_{S600}}{Y_{S75}}\right]$$

$$U_{1C,2} = (6.08 P_{L1,2} - 6.64 P_{L2,2})\, 10^{-7}$$

f. Use 6d in 6e to express displacement of 1st sleeve outer radius as a function of $P_{12,2}$ only

$$U_{1C,2} = -2.27 \times 10^{-7} P_{12,2}$$

g. Determine displacement of inner radius of 2nd sleeve due to $P_{12,2}$ at 75°F, from 4k.

$$U_{2C,2} = 9.84 \times 10^{-7} P_{12,2} \left[\frac{Y_{S600}}{Y_{S75}}\right]$$

$$U_{2C,2} = 8.48 \times 10^{-7} P_{12,2}$$

h. Add absolute values of 6f and 6g and equate to 6a. Solve for $P_{12,2}$.

$$(2.27 + 8.48)\, 10^{-7} P_{12,2} = 0.0108$$

$$P_{12,2} = 11,000 \text{ psi}$$

i. Substitute 6h in 6d to obtain $P_{L1,1}$

$$P_{L1,2} = 7,900 \text{ psi}$$

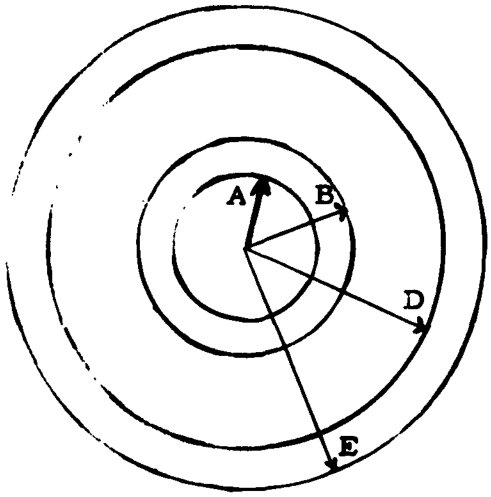
j. Calculate expansion of 2nd sleeve outer radius at 75°F due to $P_{12,2}$.

$$U_{2D,2} = \frac{2C^2DP_{12,2}}{Y_{S600}(D^2 - C^2)} = 0.0086 \text{ in.}$$

Outer radius of unstressed 2nd sleeve, at 75°F, is 2.5606 in.

Outer radius of stressed 2nd sleeve, at 75°F, is 2.5692 in.

7. Pressure Generated at Liner-First Sleeve Interface and Second-Third Sleeve Interface by Third Sleeve Shrink Fit, at 600°F



E = 2.810 in., nominal

FIG. 7 - LINER, FIRST-SECOND SLEEVE COMBINATION, AND THIRD SLEEVE ASSEMBLY

a. Determine 3rd sleeve inner radius at 1025°F which satisfies clearance requirement for 2nd sleeve stressed outer radius, at 75°F

Second sleeve outer radius, at 75°F, is 2.5692 in. when shrunk over first sleeve. When 3rd sleeve is heated to 1025°F, let there be a 0.0050 in. clearance between 2nd and 3rd sleeve. Inner radius of 3rd sleeve is then 2.5742 in., at 1025°F.

Unstressed inner radius of 3rd sleeve, at 600°F, is

$$D_{3S600} = \frac{D_{3S1025}(1 + \alpha_{S600}\Delta t_{600-75})}{1 + \alpha_{S1000}\Delta t_{1025-75}}$$

b. Determine expansion of 2nd sleeve outer radius at 600°F from interfacial pressure found in 4L

$$U_{2D2} = \frac{2C^2DP_{12,2}}{Y_{S600}(D^2 - C^2)} = 0.0075 \text{ in.}$$

c. Determine unstressed outer radius of 2nd sleeve at 600°F and add to value in 7b to obtain stressed 1st sleeve outer radius

$$C_{2S600} = C_{2S75}(1 + \alpha_{S600}\Delta t_{600-75}) = 2.5695 \text{ in.}$$

Stressed 2nd sleeve outer radius, at 600°F, is 2.5696 + 0.0075 = 2.5771 in.

d. Subtract 7c from 7a to obtain 2nd-3rd sleeve interference at 600°F

$$\beta_{23} = 2.5771 - 2.5657 = 0.0114 \text{ in.}$$

e. Determine unstressed 3rd sleeve inner radius at 75°F to obtain machining dimension

$$D_{3S75} = \frac{D_{3S1025}}{1 + \alpha_{S1000}\Delta t_{1025-75}} = 2.5566 \text{ in.}$$

Machining dimension of 3rd sleeve inner radius is 2.5566 in.

f. Determine displacement of liner at liner-1st sleeve interface in terms of interfacial pressure developed at this interface by 3rd sleeve, at 600°F

Displacement of liner at liner-1st sleeve interface due to pressure $P_{L1,3}$ at 600°F is

$$U_{LB,3} = \frac{BP_{L1,3}}{Y_{L600}}\left[\frac{A^2+B^2}{B^2-A^2} - \mu\right] = -3.11 \times 10^{-7} P_{L1,3}$$

g. Determine displacement of 1st-2nd sleeve combination at liner-1st sleeve interface in terms of pressure exerted at liner-1st sleeve interface and pressure exerted at 2nd-3rd sleeve interface by 3rd sleeve, at 600°F

$$U_{(1,2)B,3} = -\left[\frac{1-\mu}{Y_{S600}}\right]\left[\frac{B^2P_{L1,3}-D^2P_{23,3}}{D^2-B^2}\right]B + \left[\frac{1+\mu}{Y_{S600}}\right]\left[\frac{B^2D^2(P_{L1,3}-P_{23,3})}{B(D^2-B^2)}\right]$$

$$U_{(1,2)B,3} = 3.99 \times 10^{-7}P_{L1,3} - 4.56 \times 10^{-7}P_{23,3}$$

h. Equate expressions developed in 7f and 7g to obtain liner-1st sleeve interfacial pressure in terms of 2nd-3rd sleeve interfacial pressure, at 600°F

$$-3.11 \times 10^{-7}P_{L1,3} = 3.99 \times 10^{-7}P_{L1,3} - 4.56 \times 10^{-7}P_{23,3}$$

$$P_{L1,2} = 0.643\,P_{23,3}$$

i. Determine displacement of 2nd sleeve outer radius due to $P_{L1,3}$ and $P_{23,3}$

$$U_{(1,2)D,3} = \frac{1-\mu}{Y_{S600}}\left[\frac{B^2P_{L1,3} - D^2P_{23,3}}{D^2-B^2}\right]D + \frac{1+\mu}{Y_{S600}}\left[\frac{B^2D^2(P_{L1,3}-P_{23,3})}{(D^2-B^2)D}\right]$$

$$U_{(1,2)D,3} = (2.86\,P_{L1,3} - 3.14\,P_{23,3})\,10^{-7}$$

j. Substitute 7h in 7i to express displacement of 2nd sleeve outer radius as a function of $P_{23,3}$ only

$$U_{(1,2)D,3} = -1.30 \times 10^{-7}P_{23,3}$$

k. Determine displacement of inner radius of 3rd sleeve due to $P_{23,3}$

$$U_{3D,3} = \frac{DP_{23,3}}{Y_{S600}} \left[\frac{D^2 + E^2}{E^2 - D^2} + \mu \right] = 12.0 \times 10^{-7} P_{23,3}$$

l. Add absolute value of 7j and 7k and equate to 7d. Solve for $P_{23,3}$

$$(1.30 + 12.0)\, 10^{-7} P_{23,3} = 0.0114$$

$$P_{23,3} = 8,570 \text{ psi}$$

m. Substitute 7l in 7h to obtain $P_{L1,3}$

$$P_{L1,3} = 5,510 \text{ psi}$$

8. <u>Stress Generated in Liner, First-Second Sleeve Combination, and Third Sleeve, due to Second-Third Sleeve Shrink Fit, at 600°F</u>

a. Determine tangential and radial stress in liner, from 7m

$$S_{LT3} = - \frac{P_{L1,3} B^2}{B^2 - A^2} \left[1 + \frac{A^2}{r^2} \right] = -23,400 - \frac{75,700}{r^2}$$

At r = A, $S_{LT3} = -46,800$ psi

$$S_{LR3} = -23,400 + \frac{75,700}{r^2}$$

At r = A, $S_{LR3} = 0$

b. Determine tangential and radial stress in 1st-2nd sleeve combination

$$S_{(1,2)T3} = - \frac{B^2 P_{L1,3} - D^2 P_{23,3}}{D^2 - B^2} + \frac{(P_{L1,3} - P_{23,3}) C^2 D^2}{r^2 (D^2 - B^2)}$$

$$S_{(1,2)T3} = -14,300 - \frac{36,800}{r^2}$$

$$S_{(1,2)R3} = -14,300 + \frac{36,800}{r^2}$$

c. Determine tangential and radial stress in 3rd sleeve

$$S_{3T3} = \frac{D^2 P_{23,3}}{E^2 - D^2} \left[1 + \frac{E^2}{r^2} \right] = 41,600 + \frac{329,000}{r^2}$$

$$S_{3R3} = 41,600 - \frac{329,000}{r^2}$$

9. <u>Outer Radius of Stressed Third Sleeve, due to Shrink Fit, at 75°F</u>

a. Determine interference between stressed 2nd sleeve outer radius and unstressed 3rd sleeve inner radius at 75°F by use of values in 6j and 7e

$$\gamma_{23} = 2.5692 - 2.5566 = 0.0126 \text{ in.}$$

b. Determine displacement of liner at liner-1st sleeve interface in terms of interfacial pressure developed at this interface by 3rd sleeve, from 7f, at 75°F

$$U_{LB,3} = -3.11 \times 10^{-7} P_{L1,3} \left[\frac{Y_{L600}}{Y_{L75}} \right] = -3.09 \times 10^{-7} P_{L1,3}$$

c. Determine displacement of 1st-2nd sleeve combination at liner-1st sleeve interface in terms of pressure exerted at liner-1st sleeve interface, and pressure exerted by 2nd-3rd sleeve interface by 3rd sleeve, at 75°F, from results of 7g

$$U_{(1,2)B,3} = (3.99\, P_{L1,3} - 4.56\, P_{23,3})\, 10^{-7} \left[\frac{Y_{S600}}{Y_{S75}} \right]$$

$$U_{(1,2)B,3} = (2.68\, P_{L1,3} - 3.94\, P_{23,3})\, 10^{-7}$$

d. Equate expressions developed in 9b and 9c to obtain liner-1st sleeve interfacial pressure in terms of 2nd-3rd sleeve interfacial pressure, at 75°F

$$-3.09 \times 10^{-7}\, P_{L1,3} = 2.68 \times 10^{-7}\, P_{L1,3} - 3.94 \times 10^{-7} P_{23,3}$$

$$P_{L1,3} = 0.684\, P_{23,3}$$

e. Determine displacement of 2nd sleeve outer radius due to $P_{L1,3}$ and $P_{23,3}$ at 75°F, from 7i

$$U_{(1,2)D,3} = (2.86\, P_{L1,3} - 3.14\, P_{23,3})\, 10^{-7}\left[\frac{Y_{S600}}{Y_{S75}}\right]$$

$$U_{(1,2)D,3} = (2.46\, P_{L1,3} - 2.71\, P_{23,3})\, 10^{-7}$$

f. Use results of 9d in 9e to express displacement of 2nd sleeve outer radius as a function of $P_{23,3}$ only

$$U_{(1,2)D,3} = -1.03 \times 10^{-7} P_{23,3}$$

g. Determine displacement of inner radius of 3rd sleeve due to $P_{23,3}$ at 75°F from 7k

$$U_{3D,3} = 12.0 \times 10^{-7} P_{23,3}\left[\frac{Y_{S600}}{Y_{S75}}\right]$$

$$U_{3D,3} = 10.4 \times 10^{-7} P_{23,3}$$

h. Add absolute value of results of 9f and 9g and equate to 9a. Solve for $P_{23,3}$

$$(10.3 + 10.4)\, 10^{-7}\, P_{23,3} = 0.0126$$

$$P_{23,3} = 11,100 \text{ psi}$$

i. Substitute 9h in 9d to obtain $P_{L1,3}$

$$P_{L1,3} = 7,950 \text{ psi}$$

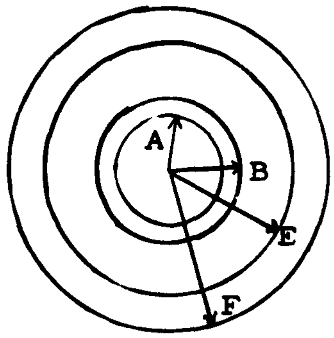
j. Calculate expansion of 3rd sleeve outer radius at 75°F due to $P_{23,3}$

$$U_{3E,3} = \frac{2D^2EP_{23,3}}{Y_{S600}(E^2 - D^2)} = 0.0105 \text{ in.}$$

Outer radius of unstressed 3rd sleeve, at 75°F, is 2.8166 in.

Outer radius of stressed 3rd sleeve, at 75°F, is 2.8271 in.

10. **Pressure Generated at Liner-First Sleeve Interface and Third-Fourth Sleeve Interface by Fourth Sleeve Shrink Fit, at 600°F**



F = 3.310 in., nominal

FIG. 8 - LINER, FIRST-SECOND-THIRD SLEEVE COMBINATION, AND FOURTH SLEEVE ASSEMBLY

a. Determine 4th sleeve inner radius at 1025°F which satisfies clearance requirement for 3rd sleeve stressed outer radius at 75°F

Third sleeve outer radius, at 75°F, is 2.8271 in. when shrunk over 2nd sleeve. When 4th sleeve is heated to 1025°F, let there be a 0.0060 in. clearance between 3rd and 4th sleeve. Inner radius of 4th sleeve is then 2.8331 in., at 1025°F.

Unstressed inner radius of 4th sleeve at 600°F is

$$E_{4S600} = \frac{E_{4S1025}(1 + \alpha_{S600}\Delta t_{600-75})}{1 + \alpha_{S1000}\Delta t_{1025-75}} = 2.8237 \text{ in.}$$

b. Determine expansion of 3rd sleeve outer radius at 600°F from interfacial pressure found in 7l

$$U_{3E3} = \frac{2D^2EP_{23,3}}{Y_{S600}(E^2 - D^2)} = 0.0092 \text{ in.}$$

c. Determine unstressed outer radius of 3rd sleeve at 600°F and add to value in 10b to obtain stressed 1st sleeve outer radius

Unstressed 3d sleeve outer radius at 600°F is,

$$C_{3S600} = C_{3S75}(1 + \alpha_{S600}\Delta t_{600-75}) = 2.8265 \text{ in.}$$

Stressed 3rd sleeve outer radius at 600°F is 2.8265 + 0.0092 = 2.8357 in.

d. Subtract 10a result from 10c result to obtain 3rd-4th sleeve interference at 600°F

$$\beta_{34} = 2.8357 - 2.8237 = 0.0120 \text{ in.}$$

e. Determine unstressed 4th sleeve inner radius at 75°F to obtain machining dimension

Unstressed 4th sleeve inner radius at 75°F is

$$E_{4S75} = \frac{E_{4S1025}}{1 + \alpha_{S1000}\Delta t_{1025-75}} = 2.8137 \text{ in.}$$

Machining dimension of 4th sleeve inner radius is 2.8137 in.

f. Determine displacement of liner at liner-1st sleeve interface in terms of interfacial pressure developed at this interface by 4th sleeve, at 600°F by use of 7f

$$U_{LB,4} = -3.11 \times 10^{-7} P_{L1,4}$$

g. Determine displacement of 1st-2nd-3rd sleeve combination at liner-1st sleeve interface in terms of pressure exerted at liner-1st sleeve interface and pressure exerted at 3rd-4th sleeve interface by 4th sleeve, at 600°F

$$U_{(1,2,3)B4} = -\left[\frac{1-\mu}{Y_{S600}}\right]\left[\frac{B^2P_{L1,4} - E^2P_{34,4}}{E^2 - B^2}\right]B + \left[\frac{1+\mu}{Y_{S600}}\right]\left[\frac{B^2D^2(P_{L1,4} - P_{34,4})}{B(E^2 - B^2)}\right]$$

$$U_{(1,2,3)B,4} = 2.94 \times 10^{-7} P_{L1,4} - 3.51 \times 10^{-7} P_{34,4}$$

h. Equate expressions developed in 10f and 10g to obtain liner-1st sleeve interfacial pressure in terms of 3rd-4th sleeve interfacial pressure, at 600°F

$$-3.11 \times 10^{-7} P_{L1,4} = (2.94 P_{L1,4} - 3.51 P_{34,4})\, 10^{-7}$$

$$P_{L1,4} = 0.580\, P_{34,4}$$

i. Determine displacement of 3rd sleeve outer radius due to $P_{L1,4}$ and $P_{34,4}$

$$U_{(1,2,3)E,4} = \frac{1-\mu}{Y_{S600}}\left[\frac{B^2P_{L1,4} - E^2P_{34,4}}{E^2 - B^2}\right] E + \frac{1+\mu}{Y_{S600}}\left[\frac{B^2E^2(P_{L1,4} - P_{34,4})}{(E^2 - B^2)E}\right]$$

$$U_{(1,2,3)E,4} = 2.57 \times 10^{-7} P_{L1,4} - 3.34 \times 10^{-7} P_{34,4}$$

j. Substitute result of 10h in 10i to express displacement of 3rd sleeve outer radius as a function of $P_{34,4}$ only

$$U_{(1,2,3)E,3} = -1.85 \times 10^{-7} P_{34,4}$$

k. Determine displacement of inner radius of 4th sleeve due to $P_{34,4}$

$$U_{4E,4} = \frac{EP_{34,4}}{Y_{S600}}\left[\frac{E^2 + F^2}{F^2 - D^2} + \mu\right] = 7.09 \times 10^{-7} P_{34,4}$$

l. Add absolute value of 10j and 10k and equate to 10d. Solve for $P_{34,4}$

$$(1.85 + 7.09)\, 10^{-7} P_{34,4} = 0.0120$$

$$P_{34,4} = 13,400 \text{ psi}$$

m. Substitute 10 l in 10h to obtain $P_{L1,4}$

$$P_{L1,4} = 7,770 \text{ psi}$$

n. Calculate expansion of 4th sleeve outer radius at 600°F due to $P_{34,4}$

$$U_{4F,4} = \frac{2E^2FP_{34,4}}{Y_{S600}(F^2 - E^2)} = 0.0090 \text{ in.}$$

o. Calculate 4th sleeve unstressed outer radius at 600°F

Inner radius of container sleeve is 3.3100 in. at 75°F. Inner radius at 600°F will be

$$F_{600} = F_{75}(1 + \alpha\Delta t_{600-75}) = 3.220 \text{ in.}$$

Set clearance between container sleeve inner radius and 4th sleeve outer radius at 0.0003 in., at 600°F. Stressed 4th sleeve outer radius is then 3.3217 in., at 600°F.

From 10n, unstressed 4th sleeve outer radius is then 3.3217 - 0.0090 = 3.3127 in., at 600°F

p. Calculate 4th sleeve unstressed outer radius at 75°F

$$F_{75} = \frac{F_{600}}{1 + \alpha\Delta t_{600-75}} = 3.3101 \text{ in.}$$

Unstressed 4th sleeve outer radius, at 75°F, is 3.3101 in.

11. <u>Stress Generated in Liner, First-Second-Third Sleeve Combination, and Fourth Sleeve Due to Third-Fourth Sleeve Shrink Fit at 600°F</u>

a. Determine tangential and radial stress in liner

$$S_{LT4} = -\frac{P_{L1,4}B^2}{B^2 - A^2}\left[1 + \frac{A^2}{r^2}\right] = -32,000 - \frac{106,000}{r^2}$$

At r = A, $S_{LT4} = -65,200$ psi

$$S_{LR4} = -32,600 + \frac{106,000}{r^2}$$

At r = A, $S_{LR4} = 0$

b. Determine tangential and radial stress in 1st-2nd-3rd sleeve combination

$$S_{(1,2,3)T4} = -\frac{B^2P_{L1,4} - E^2P_{34,4}}{E^2 - B^2} + \frac{(P_{L1,4} - P_{34,4})D^2E^2}{r^2(E^2 - B^2)}$$

$$S_{(1,2,3)T4} = -19,900 - \frac{51,500}{r^2}$$

$$S_{(1,2,3)R4} = -19,900 + \frac{51,500}{r^2}$$

c. Determine tangential and radial stress in 4th sleeve

$$S_{4T4} = \frac{E^2P_{34,4}}{F^2 - E^2}\left[1 + \frac{F^2}{r^2}\right] = 34,200 + \frac{376,000}{r^2}$$

$$S_{4R4} = 34,200 - \frac{376,000}{r^2}$$

12. Outer Radius of Stressed Fourth Sleeve Due to Shrink Fit, at 75°F

a. Determine interference between stressed 3rd sleeve outer radius and unstressed 4th sleeve inner radius at 75°F by use of 9j and 10e

$$Y_{34} = 2.8271 - 2.8137 = 0.0134 \text{ in.}$$

b. Determine displacement of liner at liner-1st sleeve interface in terms of interfacial pressure developed at this interface by 4th sleeve, from results of 10f, at 75°F,

$$U_{LB,4} = -3.11 \times 10^{-7} P_{L1,4} \left[\frac{Y_{L600}}{Y_{L75}}\right] = -3.09 \times 10^{-7} P_{L1,4}$$

c. Determine displacement of 1st-2nd-3rd sleeve combination at liner-1st sleeve interface in terms of pressure exerted at liner-1st sleeve interface, and pressure exerted by 3rd-4th sleeve interface by 4th sleeve, at 75°F, from 10g

$$U_{(1,2,3)B,4} = (2.94 P_{L1,4} - 3.51 P_{34,4}) 10^{-7} \left[\frac{Y_{S600}}{Y_{S75}}\right]$$

$$U_{(1,2,3)B,4} = (2.54 P_{L1,4} - 3.03 P_{34,4}) 10^{-7}$$

d. Equate expressions developed in 12b and 12c to obtain liner-1st sleeve interfacial pressure in terms of 3rd-4th sleeve interfacial pressure, at 75°F

$$-3.09 \times 10^{-7} P_{L1,4} = (2.54 P_{L1,4} - 3.03 P_{34,4}) 10^{-7}$$

$$P_{L1,4} = 0.540 P_{34,4}$$

e. Determine displacement of 3rd sleeve outer radius due to $P_{L1,4}$ and $P_{34,4}$ at 75°F from results of 10i

$$U_{(1,2,3)E,4} = (2.57 P_{L1,4} - 3.34 P_{34,4}) 10^{-7} \left[\frac{Y_{S600}}{Y_{S75}}\right]$$

$$U_{(1,2,3)E,4} = (2.22 P_{L1,4} - 2.88 P_{34,4}) 10^{-7}$$

f. Use result of 12d in 12e to express displacement of 3rd sleeve outer radius as a function of $P_{34,4}$ only

$$U_{(1,2,3)E,4} = -1.68 \times 10^{-7} P_{34,4}$$

g. Determine displacement of inner radius of 4th sleeve due to $P_{34,4}$ from 10k, at 75°F

$$U_{4E,4} = 7.09 \times 10^{-7} P_{34,4} \left[\frac{Y_{S600}}{Y_{S75}} \right]$$

$$U_{4E,4} = 6.11 \times 10^{-7} P_{34,4}$$

h. Add absolute value of results of 12f and 12g and equate to 12a. Solve for $P_{34,4}$

$$(1.68 + 6.11) \times 10^{-7} P_{34,4} = 0.0134$$

$$P_{34,4} = 17,200 \text{ psi}$$

i. Substitute 12h in 12d to obtain $P_{L1,4}$

$$P_{L1,4} = 9,300 \text{ psi}$$

j. Calculate expansion of 4th sleeve outer radius at 75°F due to $P_{34,4}$

$$U_{4F,4} = \frac{2E^2FP_{34,4}}{Y_{S75}(F^2 - E^2)} = 0.0099 \text{ in.}$$

k. Calculate stressed 4th sleeve outer radius at 75°F by adding 10p and 12j

$$F_{4E} = 3.3101 + 0.0099 = 3.3200 \text{ in.}$$

Since container sleeve inner radius is 3.3100 in. at 75°F, a 0.0100 in. interference will be developed between 4th sleeve outer radius and container sleeve inner radius at 75°F.

13. Stress Developed in Liner-Sleeve Assembly Due to Combined Action of Shrink Fits, at 600°F

a. Determine tangential and radial stress in liner by adding appropriate equations in 2c, 5a, 8a, 11a

$$S_{LT1} + S_{LT2} + S_{LT3} + S_{LT4} = -116,000 - \frac{376,000}{r^2}; \quad A \leq r \leq B$$

$$S_{LR1} + S_{LR2} + S_{LR3} + S_{LR4} = -116,000 + \frac{376,000}{r^2}$$

b. Determine tangential and radial stress in 1st sleeve by adding appropriate equations in 2d, 5b, 8b, 11b

$$S_{1T1} + S_{1T2} + S_{(1,2)T3} + S_{(1,2,3)T4} = -20,200 + \frac{29,900}{r^2}; \quad B \leq r \leq C$$

$$S_{1R1} + S_{1R2} + S_{(1,2)R3} + S_{(1,2,3)R4} = -20,200 - \frac{29,900}{r^2}$$

c. Determine tangential and radial stress in 2nd sleeve by adding appropriate equations in 5c, 8b, 11b

$$S_{2T2} + S_{(1,2)T3} + S_{(1,2,3)T4} = 2,800 + \frac{154,000}{r^2} \qquad C \leq r \leq D$$

$$S_{2R2} + S_{(1,2)R3} + S_{(1,2,3)R4} = 2,800 - \frac{154,000}{r^2}$$

d. Determine tangential and radial stress in 3rd sleeve by adding appropriate equations in 8c, 11b

$$S_{3T3} + S_{(1,2,3)T4} = 21,700 + \frac{277,500}{r^2} \qquad D \leq r \leq E$$

$$S_{3R3} + S_{(1,2,3)R4} = 21,700 - \frac{277,500}{r^2}$$

e. Determine tangential and radial stress in 4th sleeve from 11c

$$S_{4T4} = 34,200 + \frac{376,000}{r^2} \qquad D \leq r \leq E$$

$$S_{4R4} = 34,200 - \frac{376,000}{r^2}$$

Equations developed in section 13 are plotted in Fig. 9 to show stress due to shrink fitting as a function of radial distance in liner and each sleeve.

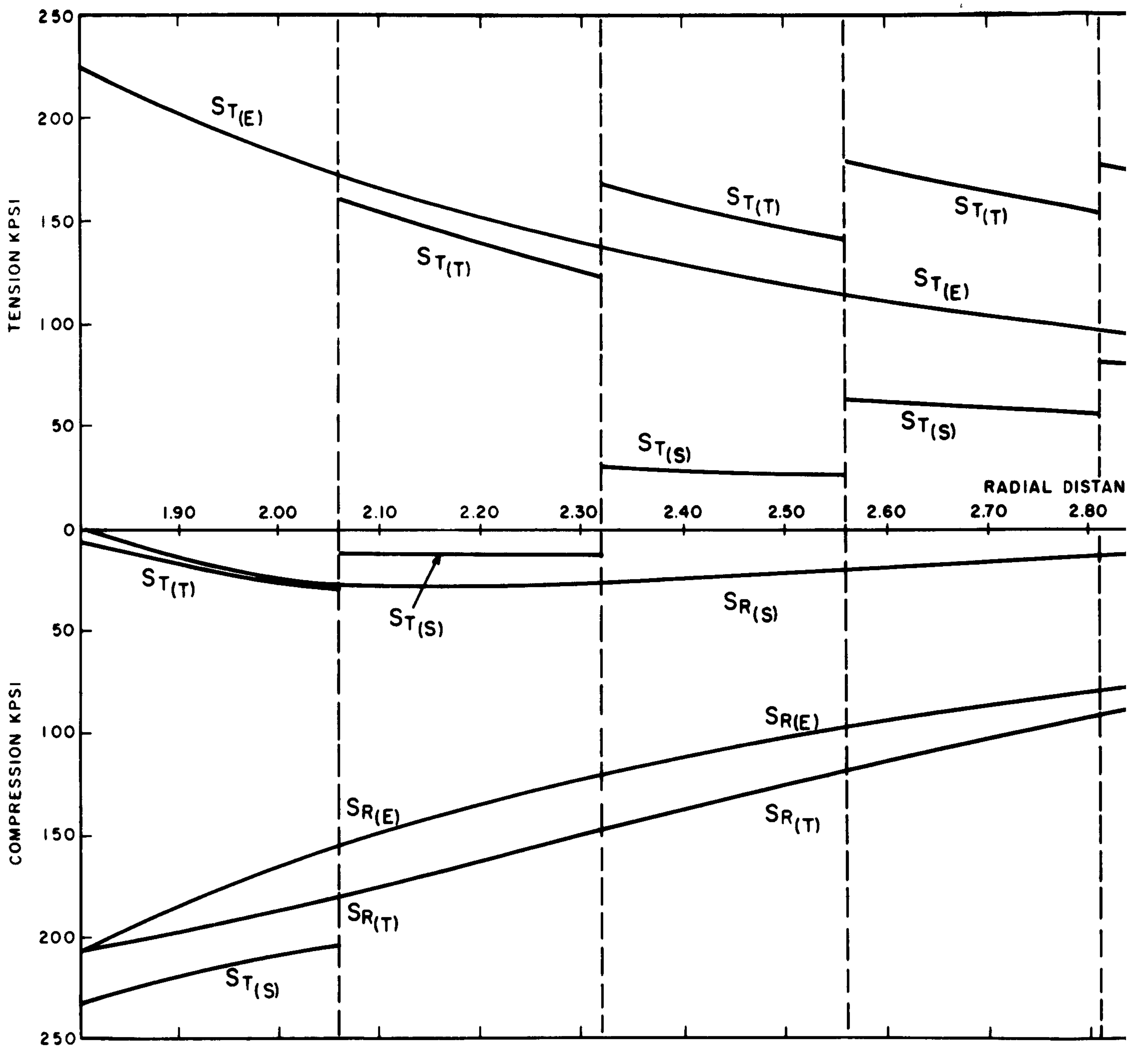
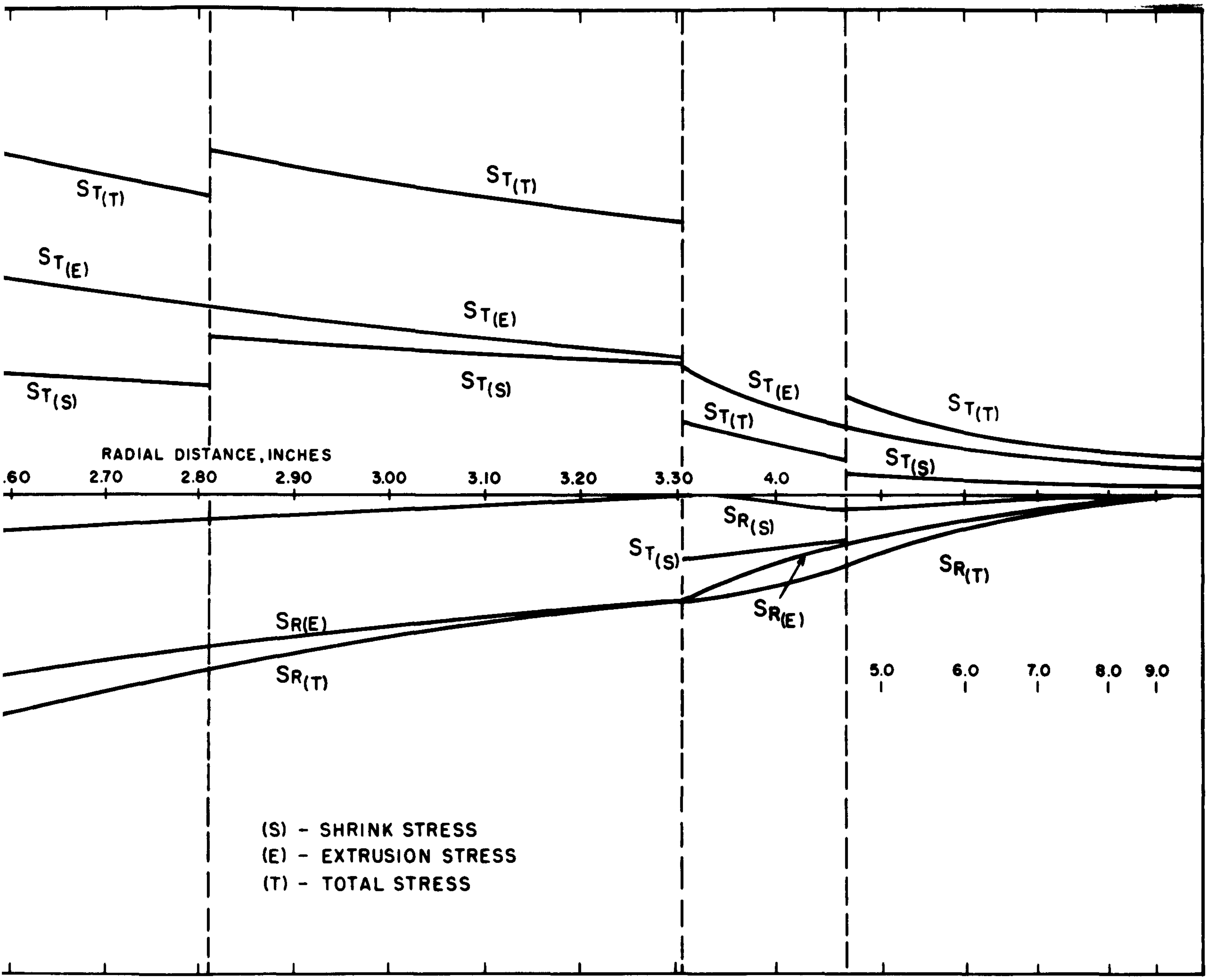


FIG. 9 LINER SLEEVE AND CONTAINER STRESS FOR FOUR SLEEVE ASSEMBLY AS

2



LEEVE ASSEMBLY AS A FUNCTION OF RADIAL DISTANCE FROM CONTAINER CENTERLINE

)45 (II)

14. Calculation of Peak Tangential Stress in Liner Due to Combined Shrink Fits, at 75°F

a. Add liner-1st sleeve interfacial pressures developed by 1st, 2nd, 3rd, and 4th sleeves at 75°F. Values are found in 3d, 6i, 9i, 12i. Calculate stress in inner radius of liner

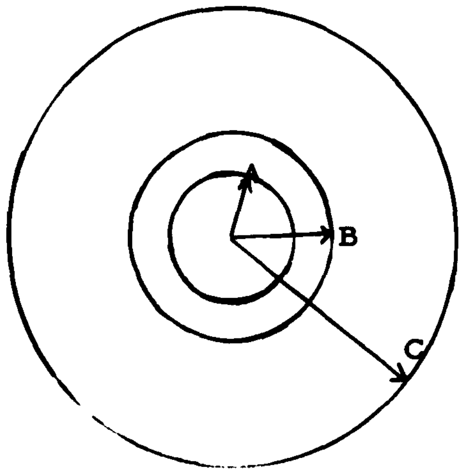
$$S_{LT(1,2,3,4)} = -\frac{2B^2}{B^2 - A^2}(P_{L1,1} + P_{L1,2} + P_{L1,3} + P_{L1,4})$$

$$S_{LT(1,2,3,4)} = -304,000 \text{ psi, at } 75°F$$

Ultimate compressive strength of the alumina liner is 340,000 psi. Hence, liner and sleeve assembly may be stored at room temperature, when not in service.

Section 12k shows that a 0.010 interference fit will develop between 4th sleeve outer radius and container sleeve inner radius, at 75°F. The additional compressive stress placed on the liner by this condition is likely to cause liner failure, since this stress adds to the 304,000 psi compressive stress already existing. Therefore, it will be necessary to remove liner-sleeve assembly from the container before container is allowed to cool. The 0.0001-0.0005 in clearance between 4th sleeve outer radius and container sleeve inner radius should enable removal of this assembly at 600°F without difficulty.

15. Extrusion Stress on Liner and Sleeves when Fourth Sleeve Outer Radius is Expanded 0.0005 in., at 600°F



$P_{A,el}$ = stem pressure required to expand 4th sleeve outer radius 0.0005 in.

FIG. 10 - LINER AND FIRST-SECOND-THIRD-FOURTH COMBINATION SLEEVE ASSEMBLY

a. Determine displacement of liner outer radius in terms of extrusion pressure on liner inner radius and liner-1st sleeve interfacial pressure

$$U_{LB, el} = \frac{1-\mu}{Y_{L600}} \left[\frac{A^2 P_{A, el} - B^2 P_{B, el}}{B^2 - A^2} \right] B + \frac{1+\mu}{Y_{L600}} \left[\frac{A^2 B^2 (P_{A, el} - P_{B, el})}{(B^2 - A^2) B} \right]$$

$$U_{LB, el} = 2.80 \times 10^{-7} P_{A, el} - 3.10 \times 10^{-7} P_{B, el}$$

b. Determine displacement of 1st-2nd-3rd-4th sleeve combination at 1st sleeve inner radius, in terms of liner-1st sleeve interfacial pressure

$$U_{(1, 2, 3, 4)B, el} = \frac{BP_{B, el}}{Y_{S600}} \left[\frac{B^2 + F^2}{F^2 - B^2} + \mu \right]$$

$$U_{(1, 2, 3, 4)B, el} = 2.09 \times 10^{-7} P_{B, el}$$

c. Equate 15a and 15b to obtain liner-1st sleeve interfacial pressure as a function of extrusion pressure at liner inner radius

$$2.80 P_{A, el} - 3.10 P_{B, el} = 2.09 P_{B, el}$$

$$P_{A, el} = 1.85 P_{B, el}$$

d. Express 0.0005 in. expansion of 4th sleeve outer radius in terms of liner-1st sleeve interfacial pressure. Determine pressure.

Displacement of 1st-2nd-3rd-4th sleeve combination at 4th sleeve outer radius due to $P_{B, el}$ is

$$U_{(1, 2, 3, 4)F, el} = \frac{2B^2 F P_{B, el}}{Y_{S600}(F^2 - B^2)} = 0.0005 \text{ in.}$$

$$P_{B, el} = 3,050 \text{ psi}$$

e. Substitute 15d in 15c to obtain stem pressure

$$P_{A, el} = 5,650 \text{ psi}$$

f. Determine tangential and radial stress generated by extrusion pressure at inner radii of liner and all sleeves

$$S_{(L,1,2,3,4)Tel} = \frac{A^2 P_{A,\,el}}{F^2 - A^2}\left[1 + \frac{F^2}{r^2}\right] \qquad A \leq r \leq F$$

$$S_{(L,1,2,3,4)Tel} = 2,360 + \frac{26,000}{r^2}$$

$$S_{(L,1,2,3,4)Rel} = 2,360 - \frac{26,000}{r^2}$$

16. <u>Stress Developed in Liner-Sleeve Assembly by 207,000 psi Stem Pressure, at 600°F</u>

a. Subtract extrusion pressure in 15e from total pressure, and determine tangential and radial stress for this pressure

$$P_{A,\,e2} = 207,000 - 5,650 \cong 201,000 \text{ psi}$$

$$S_{(L,1,2,3,4)Te2} = \frac{A^2 P_{A,\,e2}}{M^2 - A^2}\left[1 + \frac{M^2}{r^2}\right] \qquad A \leq r \leq M$$

$$S_{(L,1,2,3,4)Te2} = 6,730 + \frac{673,000}{r^2}$$

$$S_{(L,1,2,3,4)Re2} = 6,730 - \frac{673,000}{r^2}$$

b. Determine total stress by adding results of 15f and 16a

$$S_{(L,1,2,3,4)T(el,\,e2)} = 9,090 + \frac{699,000}{r^2}$$

$$S_{(L,1,2,3,4)R(el,\,e2)} = 9,090 - \frac{699,000}{r^2}$$

Equations developed in 16b are plotted in Figure 9 to show stress due to extrusion pressure as a function of radial distance in liner and each sleeve.

17. **Stress Developed in Liner-Sleeve Assembly Due to Combined Shrink Stresses and 207,000 psi Stem Pressure**

a. Add appropriate equations in 13a to those in 16b for liner stress

$$S_T = -106,000 + \frac{323,000}{r^2} \qquad A \leq r \leq B$$

$$S_R = -106,000 - \frac{323,000}{r^2}$$

b. Add appropriate equations in 13b to those in 16b for 1st sleeve stress

$$S_T = -11,100 + \frac{729,000}{r^2} \qquad B \leq r \leq C$$

$$S_R = -11,100 - \frac{729,000}{r^2}$$

c. Add appropriate equations in 13c to those in 16b for 2nd sleeve stress

$$S_T = 11,900 + \frac{853,000}{r^2} \qquad C \leq r \leq D$$

$$S_R = 11,900 - \frac{853,000}{r^2}$$

d. Add appropriate equations in 13d to those in 16b for 3rd sleeve stress

$$S_T = 30,800 + \frac{976,000}{r^2} \qquad D \leq r \leq E$$

$$S_R = 30,800 - \frac{976,000}{r^2}$$

e. Add appropriate equations in 13e to those in 16b for 4th sleeve stress

$$S_T = 43,300 + \frac{1,075,000}{r^2} \qquad E \leq r \leq F$$

$$S_R = 43,300 - \frac{1,075,000}{r^2}$$

Equations developed in 17 are plotted in Figure 9 to show total stress as a function of radial distance in liner and each sleeve.

18. Maximum Permissible τ_o Value for Liner and Sleeves

a. Calculate maximum τ_o value for liner, using Sturm criterion

$\tau_{o,max}$ is 0.707 of the tensile strength of material, if material is brittle. Alumina liner is brittle, and has a tensile strength of 21,000 psi at 600°F.

$\tau_{o,max}$ is (0.707)(21,000) = 14,800 psi

b. Calculate maximum τ_o value for sleeves, using Sturm criterion

$\tau_{o,max}$ is 0.707 of the maximum working tensile stress of the material, if material is ductile. The maximum working tensile stress of the HTB-2 steel is taken as 75% of the 0.2% offset yield strength. At 600°F, this value is 225,000 psi.

$\tau_{o,max}$ is (0.707)(225,000) = 159,000 psi

$\tau_{o,max}$ is 159,000 psi

19. Calculation of Peak τ_o Value in Liner and Each Sleeve Under Combined Shrink Stresses and 210,000 psi Stem Pressure

a. Calculate peak τ_o value in liner and each sleeve by the equation

$$\tau_o = \frac{(0.1755\ S_T^2 + 0.1755\ S_T^2 - 0.3155\ S_T S_R)^{1/2}}{1 - \dfrac{0.433\,(S_T + S_R)}{S_o}}$$

where S_o = 21,000 for alumina

S_o = 225,000 for HTB-2

Peak τ_o value is at inner radius of each cylinder.

Calculated values of τ_o for inner radius of liner and each sleeve are listed in Table IV. It may be seen that all τ_o values are below maximum allowable under a 210,000 psi stem pressure, corresponding to a 16.7% extrusion pressure overload.

TABLE IV

PEAK τ_o VALUES FOR LINER AND EACH SLEEVE, UNDER COMBINED SHRINK STRESS AND 210,000 PSI STEM PRESSURE, FOR FOUR-SLEEVE ASSEMBLY

Part	Radius (r), in.	Tangential Stress (S_T), kpsi	Radial Stress (S_R), kpsi	Equivalent Shear Stress in Tension (τ_o), kpsi	Maximum Allowable τ_o, kpsi
Liner	1.80	- 5.0	-207	11.8	14.8
1st Sleeve	2.06	161	-183	134	159
2nd Sleeve	2.32	170	-147	135	159
3rd Sleeve	2.56	181	-118	139	159
4th Sleeve	2.81	179	- 94.9	134	159

b. Calculate peak τ_o value for liner at 75°F under zero extrusion pressure

$$\tau_o = 17,600 \text{ psi, at } 75°F$$

This value is above the maximum allowable. Consequently liner-sleeve assembly should be stored above room temperature. It is noted that both peak tangential stress and the τ_o value are higher when the liner is at 75°F under a zero extrusion load, than at 600°F under a 15% extrusion pressure overload.

20. <u>Calculation of Required Force and Pressure for Separation of Liner-Sleeve Assembly with Liner in Place</u>

a. General Approach

Liner-sleeve assembly cannot be separated by differential heating due to relatively low thermal conductivity coefficient of ceramic liner, geometry of assembly, and relatively high interference values. Instead, sleeves must be pressed off one another. This may be accomplished by either chipping out liner first, then pressing off outer sleeves successively, or pressing off outer sleeves successively without first removing liner.

If ceramic liner can be removed before sleeves are separated, sleeve interfacial pressure is reduced, and assembly may be separated at room temperature as readily as at 600°F, since all sleeve thermal expansion coefficients are the same.

If ceramic liner cannot be removed, sleeve separation should proceed at as high a temperature as possible, because sleeve interfacial pressures increase as temperature decreases. The fourth sleeve may readily be removed when assembly is at 600°F, by simply pressing liner and inner sleeves when assembly is in container sleeve. (Fourth sleeve should be supported at base to prevent an excessive load on sleeve flange when this operation is carried out.) First, second, and third sleeves may be expected to be at a lower temperature during separation, since they would not ordinarily be in contact with a heated surface during this operation.

To assure calculated separation forces are conservative, it is assumed that third, second, and first sleeve separation will be effected at 75°F. It will be seen that all sleeve removal pressure will still be below 50 tsi.

b. Calculate separation force and pressure with liner in place. Use 3d, 6h, 9h, 10m for interfacial pressures

$$F = 2\pi\nu L r_i P_i = 12.7\, r_i P_i$$

$$P = \frac{2\nu L r_i P_i}{r_o^2 - r_i^2} = \frac{4.04\, r_i P_i}{r_o^2 - r_i^2}$$

P_i = interfacial pressure
F = removal force
P = removal pressure
r_i = cylinder inner radius
r_o = cylinder outer radius
L = cylinder length, 10.1 in.
ν = coefficient of friction, 0.2

Values of required removal force and pressure for each sleeve are given in Table V.

21. Calculation of Required Force and Pressure for Separation of Liner-Sleeve Assembly with Liner Removed, at 75°F

a. Calculate interference between 1st sleeve outer radius and 2nd sleeve inner radius from dimensions given in 3e and 4e

$$\gamma_{12} = 2.3049 - 2.3006 = 0.0043 \text{ in.}$$

b. Determine interfacial pressure between 1st sleeve outer radius and 2nd sleeve inner radius

$$P_{12,2} = \frac{Y_{S75}\gamma_{12}(C^2 - B^2)(D^2 - C^2)}{2C^3(D^2 - B^2)} = 2{,}910 \text{ psi}$$

c. Determine expansion of 2nd sleeve outer radius due to 1st-2nd sleeve interfacial pressure

$$U_{2D,2} = \frac{2C^2 D P_{12,2}}{Y_{S75}(D^2 - C^2)} = 0.0023 \text{ in.}$$

d. Determine interference between stressed 2nd sleeve outer radius and unstressed 3rd sleeve inner radius from 7e and 21c

$$\gamma_{23} = 2.5606 + 0.0023 - 2.5566 = 0.0063 \text{ in.}$$

e. Determine interfacial pressure between 2nd sleeve outer radius and 3rd sleeve inner radius

$$P_{23,3} = \frac{Y_{S75}\,\gamma_{23}(D^2 - B^2)(E^2 - D^2)}{2D^3(E^2 - B^2)} = 4{,}650 \text{ psi}$$

TABLE V

REQUIRED REMOVAL FORCE AND PRESSURE FOR EACH SLEEVE WITH LINER IN PLACE, FOR FOUR-SLEEVE ASSEMBLY

Sleeve No.	Interfacial Pressure, psi	Removal Force, tons	Removal Pressure, psi
4	13,400	240	49,000
3	11,100	180	85,000
2	11,000	162	88,200
1	11,000	144	80,300

TABLE VI

REQUIRED REMOVAL FORCE AND PRESSURE FOR EACH SLEEVE WITH LINER REMOVED, FOR FOUR-SLEEVE ASSEMBLY

Sleeve No.	Interfacial Pressure, psi	Removal Force, tons	Removal Pressure, psi
4	8,080	144	29,600
3	4,650	76	35,600
2	2,910	43	23,300

f. Determine expansion of 3rd sleeve outer radius due to 2nd-3rd sleeve interfacial pressure

$$U_{3E,\,3} = \frac{2D^2 E P_{23,\,3}}{Y_{S75}(E^2 - D^2)} = 0.0044 \text{ in.}$$

g. Determine interference between stressed 3rd sleeve outer radius and unstressed 4th sleeve inner radius, using 21f

Unstressed 3rd sleeve outer radius, at 75°F, is 2.8166 in.
Unstressed 4th sleeve inner radius, at 75°F, is 2.8137 in.

$$Y_{34} = 2.8166 + 0.0044 - 2.8137 = 0.0073 \text{ in.}$$

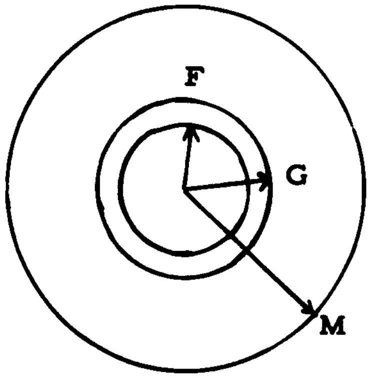
h. Determine interfacial pressure between 3rd sleeve outer radius and 4th sleeve inner radius

$$P_{34,\,4} = \frac{Y_{S75}\, Y_{34}(E^2 - B^2)(F^2 - E^2)}{2E^3(F^2 - B^2)} = 8{,}080 \text{ psi}$$

i. Substitute interfacial pressures in 21b, 21e, 21h, in equations in 20b to calculate separation force and pressure for successive removal of outer sleeves.

Results are listed in Table VI. Tables V and VI show that liner removal will considerably reduce removal pressures, but is not necessary to effect sleeve separation.

22. <u>Calculation of Container Sleeve Stresses</u>



$F = 3.310$ in., nominal

$G_L = 4.682$ in.

$M = 10.0$ in.

FIG. 11 - CONTAINER AND SLEEVE ASSEMBLY

a. General Approach

Sleeve outer radius is stepped (see Fig. 2). Shrink and extrusion stresses will be calculated for the smaller outer radius, because stresses will be largest at this point.

Both container sleeve and container have approximately the same elastic modulus and linear thermal expansion coefficient, permitting considerable simplification of calculation procedure.

Container sleeve is designed to be removed from container by maintaining sleeve inner radius at the steam point as container is heated. Sleeve outer radius is silver plated with 0.001-0.0015 in. thickness of silver to facilitate heat transfer.

b. Determine interfacial pressure between container sleeve (fifth sleeve) and container due to a radial interference of 0.0060 in.

$$P_{5C,C} = \frac{Y_{S600}\beta_{5C}(G^2 - F^2)(M^2 - G^2)}{2G^3(M^2 - F^2)} = 7,000 \text{ psi}$$

c. Determine stress on container sleeve due to shrink fit

$$S_{5TC} = -\frac{P_{5C,C}G^2}{G^2 - F^2}\left[1 + \frac{F^2}{r^2}\right] \qquad F \leq r \leq G$$

$$S_{5TC} = -16,000 - \frac{176,000}{r^2}$$

$$S_{5RC} = -16,000 + \frac{176,000}{r^2}$$

d. Determine stress on container sleeve due to 210,000 psi stem pressure

Liner-sleeve assembly expansion will absorb effect of 5,650 psi stem pressure. Accordingly, container sleeve will react to a liner pressure of approximately 204,000 psi.

$$S_{5Te2} = \frac{A^2P_{e2}}{M^2 - A^2}\left[1 + \frac{M^2}{r^2}\right] \qquad F \leq r \leq G$$

$$S_{5Te2} = 6,830 + \frac{683,000}{r^2}$$

$$S_{5Re2} = 6,830 - \frac{683,000}{r^2}$$

e. Determine effect of combined shrink and extrusion stress on container sleeve by adding appropriate equations in 22a and 22d

$$S_{5TC,e2} = -9,170 + \frac{507,000}{r^2} \qquad F \leq r \leq G$$

$$S_{5Rc,e2} = -9,170 - \frac{507,000}{r^2}$$

Equations developed in section 22 are plotted in Figure 9 to show stress due to shrink fitting and extrusion pressure as a function of radial distance in container sleeve.

f. Calculate Peak τ_o value in Container Sleeve

Peak octahedral shear stress, and peak τ_o, will be at container sleeve inner radius. There is no axial stress at this point, due to slip fit of 4th sleeve. Octahedral shear stress then becomes.

$$\tau = 0.47(S_1^2 + S_2^2 - S_1S_2)^{1/2}$$

The 0.2% offset yield strength of H-13 steel at R_c 50-52 is approximately 220,000 psi at 600°F. Let the maximum working tensile stress S_o be 75% of this value, or S_o = 165,000 psi. The τ_o value in container sleeve is given by

$$\tau_{o,peak} = \frac{\tau}{1 - \dfrac{S_1 + S_2 + S_3}{3S_o}} \quad \frac{0.47(S_1^2 + S_3^2)^{1/2}}{1 - 0.202(S_1 + S_2)10^{-5}} = 36,500 \text{ psi}$$

g. Compare 22f result with maximum permissible τ_o value calculated by Sturm criterion

$$\tau_{o,max} \leq 0.707\, S_o = 106,500 \text{ psi}$$

Peak τ_o value in container sleeve is considerably below this value.

23. Temperature Differential and Electric Heating Power Required to Remove Container Sleeve from Container

a. General Approach

Calculation will be carried out for lower section of sleeve, where interfacial pressures are the highest.

Temperature will be assumed zero at container sleeve-container interface for ease of calculation. The t_1 temperature at r = F, and

t_3 temperatures at r = M will then be relative to zero interfacial temperature. As such, only the difference between t_1 and t_3 temperatures has meaning.

b. Calculation of container sleeve-container separation temperature differential

$$t_3 = \frac{-\beta_{5C}}{a_S G\left[\frac{M^2}{M^2 - G^2} - \frac{F^2}{G^2 - F^2}\left(\frac{\ln(G/F)}{\ln(M/G)}\right)\right]} = 220°$$

$$t_1 = -\frac{t_3 \ln(G/F)}{\ln(M/G)} = -100°$$

$$t_3 - t_1 = 320°F$$

If container sleeve inner radius is held at 212°F, container outer diameter must be held at 532°F to separate sleeve from container.

c. Calculation of electric heating power required to maintain separation temperature differential

$$W = \frac{12.8 \times 10^{-6} LK\Delta t}{\ln(M/E)} \qquad L = 10.1 \text{ in.}$$

$$K = 197 \text{ Btu/ft}^2\text{/in/hr/}°F$$

W = 7.36 kilowatts

Container heaters are rated at 12.0 kilowatts.

24. Calculation of Container Stresses

a. General Approach

Inner radius of container is stepped as shown in Figure 2. Stresses due to container sleeve shrink and extrusion pressure will be greater in lower section of container. Therefore, tangential and radial stress will be calculated for this section.

b. Determine stress due to shrink of container sleeve

$$S_{CTC} = \frac{G^2 P_{5C}}{M^2 - G^2}\left[1 + \frac{M^2}{r^2}\right] \qquad G \leq r \leq M$$

$$S_{CTC} = 1,950 + \frac{195,000}{r^2}$$

$$S_{CRC} = 1,950 - \frac{195,000}{r^2}$$

c. Determine stress due to 210,000 psi stem pressure.

Liner-sleeve assembly expansion will absorb effect of 5,650 psi stem pressure. Accordingly, container will react to a liner pressure of approximately 204,000 psi.

$$S_{CTe2} = - \frac{A^2 P_{e2}}{M^2 - A^2} \left[1 + \frac{M^2}{r^2} \right] \qquad G \leq r \leq M$$

$$S_{CTe2} = 6,850 + \frac{685,000}{r^2}$$

$$S_{CRe2} = 6,850 - \frac{685,000}{r^2}$$

d. Determine effect of combined shrink and extrusion stress on container by adding appropriate equations in 23b and 23c.

$$S_{CTC, e2} = 8,800 + \frac{880,000}{r^2}$$

$$S_{CRC, e2} = 8,800 - \frac{880,000}{r^2}$$

Peak tangential stress is 50,500 psi.

Equations developed in Section 24 are plotted in Figure 9 to show stress due to shrink fitting and extrusion pressure as a function of radial distance in container.

DESIGN 2: 1000-TON PRESS CONTAINER CALCULATION FOR A LINER WITH BALANCED TENSION AND COMPRESSION STRESSES AT 0.5 OF MAXIMUM EXTRUSION PRESSURE

A. Design Procedure

1. Calculation of Shrink Stress at Liner Inner Radius, Numerically Equal to 0.5 of Maximum Extrusion Stress

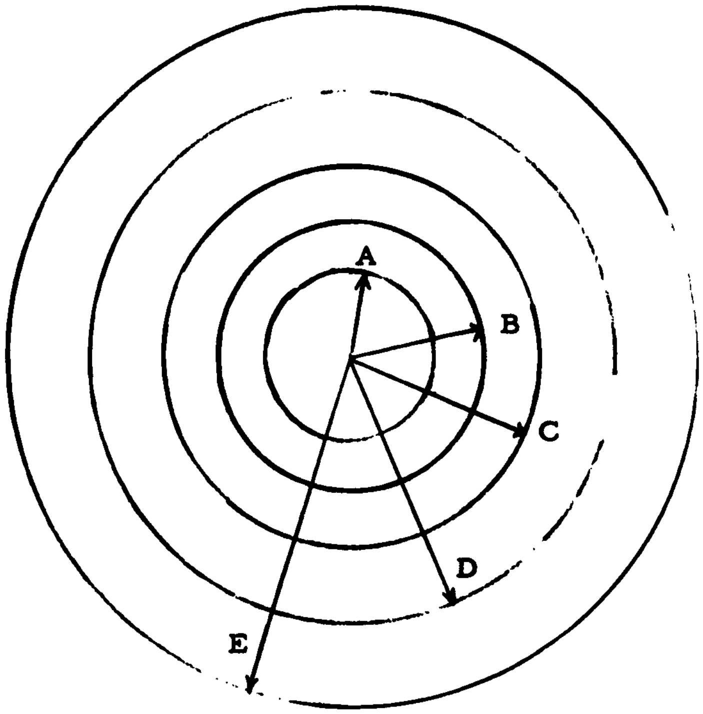


FIG. 12 - LINER AND THREE-SLEEVE ASSEMBLY

A	=	1.800 in., nominal	$U_{4D, 1e}$	=	0.0005 in.
B	=	2.060 in., nominal	Y_{75}	=	30.2×10^6 psi
C	=	2.440 in., nominal	Y_{800}	=	26.2×10^6 psi
D	=	2.810 in., nominal	α_{75}	=	$6.7 \times 10^{-6}/°F$
E	=	3.310 in., nominal	α_{800}	=	$7.2 \times 10^{-6}/°F$
			α_{1000}	=	$7.4 \times 10^{-6}/°F$

a. Calculate maximum tangential stress developed at liner inner radius by extrusion pressure. Set shrink stress equal to 0.5 of absolute value.

Let maximum extrusion pressure be 210,000 psi. The tangential stress developed at liner inner radius will be

$$S_{L\,T_{el,\ e2}} = \frac{(P_{el} + P_{e2})(A^2 + M^2)}{M^2 - A^2} = 224,000 \text{ psi}$$

If tensile and compressive tangential stresses are to balance at 0.5 maximum extrusion pressure, compressive tangential stress at liner inner radius at zero extrusion pressure must be -112,000 psi, when all sleeves are in contact.

2. Extrusion Stress on Liner and Sleeves when Third Sleeve Outer Radius is Expanded 0.0005 in.

a. Determine extrusion pressure as a function of 4th sleeve displacement, and calculate value of this pressure for 0.0005 in. displacement

$$P_{1e} = \frac{U_{4D,\ 1e} Y_{800}(E^2 - A^2)}{2A^2E} = 4,750 \text{ psi}$$

b. Calculate tangential and radial stress as a function of radial distance throughout liner-sleeve assembly

$$S_{(L,1,2,3)Tel} = \frac{A^2P_{el}}{E^2 - A^2}\left[1 + \frac{E^2}{r^2}\right]$$

$$S_{(L,1,2,3)Tel} = 1,980 + \frac{21,800}{r^2}$$

$$S_{(L,1,2,3)Rel} = 1,980 - \frac{21,800}{r^2}$$

3. Stress Developed in Liner-Sleeve Assembly by 210,000 psi Stem Pressure, at 800°F

a. Substract extrusion pressure in 2a from total pressure, and determine tangential and radial stress for this pressure

$$P_{A,\ e2} = 210,000 - 4.750 = 205,000 \text{ psi}$$

$$S_{(L,1,2,3)Te2} = \frac{A^2P_{e2}}{M^2 - A^2 2}\left[1 + \frac{M^2}{r^2}\right]$$

$$S_{(L,1,2,3)Te2} = 6,860 + \frac{686,000}{r^2}$$

$$S_{(L,1,2,3)Re2} = 6,860 - \frac{686,000}{r^2}$$

4. **Total Tangential and Radial Stress in Liner and Sleeve Assembly Due to Extrusion Pressure**

a. Add appropriate equations in 2b and 3a

$$S_{(L,1,2,3)T(e_1e_2)} = 8,840 + \frac{708,000}{r^2} \qquad A \leq r \leq E$$

$$S_{(L,1,2,3)R(e_1e_2)} = 8,840 - \frac{708,000}{r^2}$$

Equations developed in 4a are plotted in Figure 13 to show stress due to extrusion pressure as a function of radial distance in liner and each sleeve.

5. **Sleeve Interfacial Pressures Due to Shrink Stresses**

a. Express tangential stress at liner inner radius and each sleeve inner radius as a function of interfacial pressures

Liner stress, at r = A, is

$$S_{(AT,1,2,3)} = \frac{2P_{L1}B^2}{B^2 - A^2} - \frac{2P_{12}C^2}{C^2 - A^2} - \frac{2P_{23}D^2}{D^2 - A^2}$$

$$S_{(AT,1,2,3)} = 8.48\,P_{L1} + 4.37\,P_{12} + 3.39\,P_{23}$$

First sleeve stress, at r = B, is

$$S_{(BT,1,2,3)} = \frac{B^2 + C^2}{C^2 - B^2}\,P_{L1} - \left[1 + \frac{A^2}{B^2}\right]\frac{C^2P_{12}}{C^2 - A^2} - \left[1 + \frac{A^2}{B^2}\right]\frac{D^2P_{23}}{D^2 - A^2}$$

$$S_{(BT,1,2,3)} = 5,89\,P_{L1} - 3.85\,P_{12} - 2.99\,P_{23}$$

Second sleeve stress, at r = C, is

$$S_{(CT,1,2,3)} = \frac{C^2 + D^2}{D^2 - C^2}\,P_{12} - \left[1 + \frac{A^2}{C^2}\right]\frac{D^2P_{23}}{D^2 - A^2}$$

$$S_{(CT,2,3)} = 7.23\,P_{12} - 2.62\,P_{23}$$

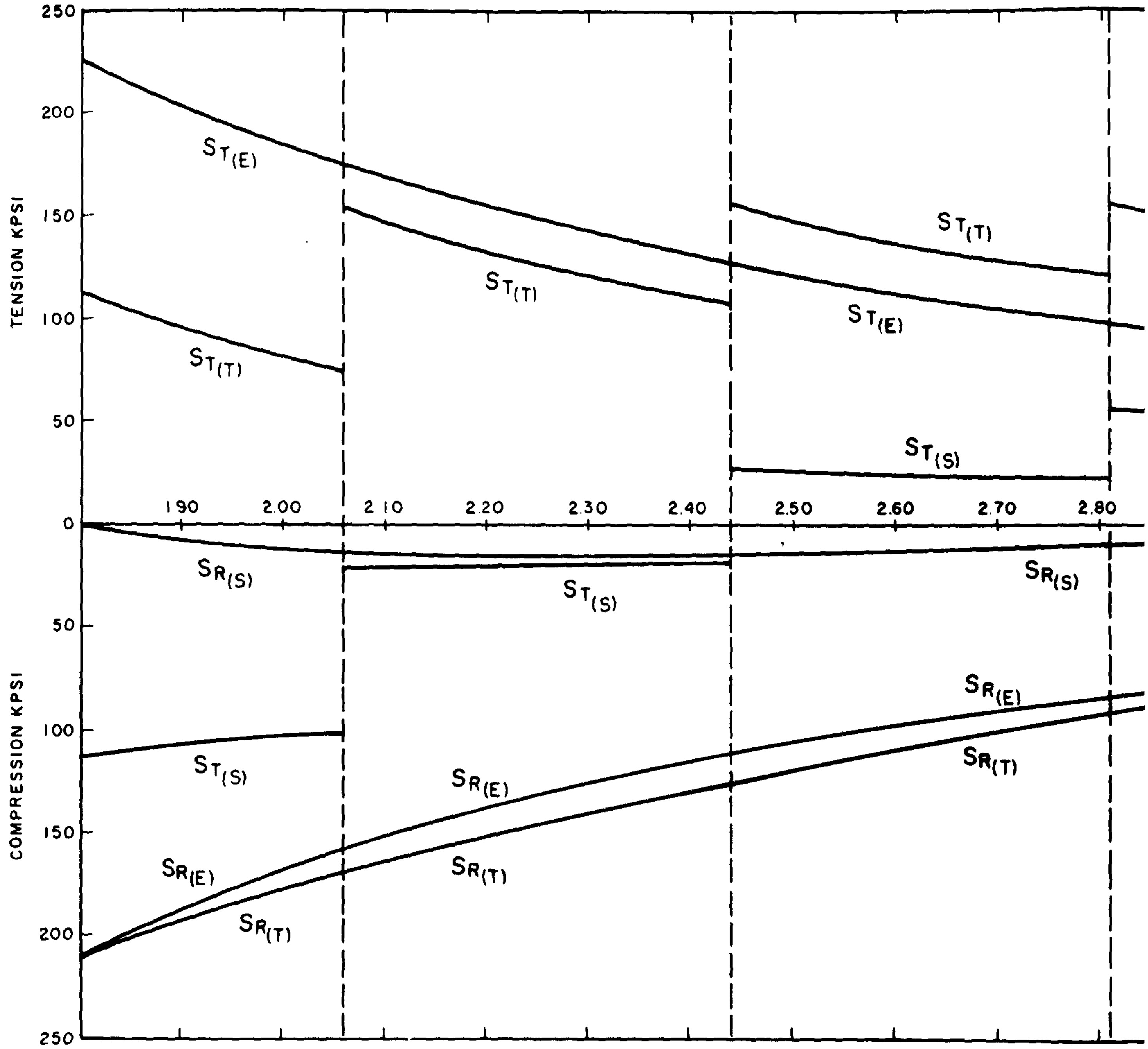


FIG. 13 LINER SLEEVE AND CONTAINER STRESS FOR THREE SLEEVE ASSEMBI

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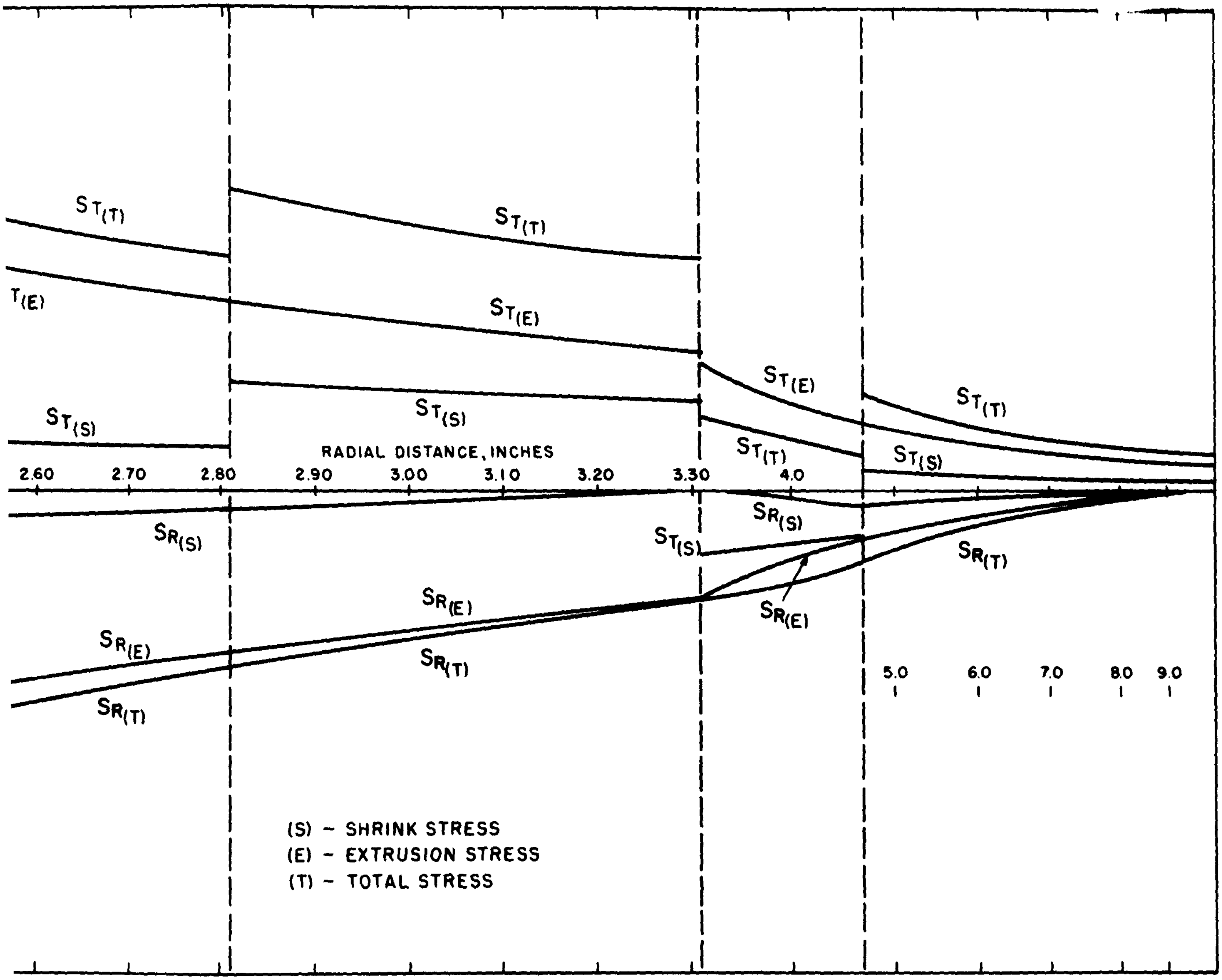

THREE SLEEVE ASSEMBLY AS A FUNCTION OF RADIAL DISTANCE FROM CONTAINER CENTERLINE

-945 (II)

Third sleeve stress, at r = D, is

$$S_{(DT,3)} = \frac{D^2 + E^2}{E^2 - D^2} P_{23}$$

$$S_{(DT,3)} = 6.10\ P_{23}$$

b. Calculate tangential stress due to extrusion pressure at liner inner radius and each sleeve inner radius, from 4a

At r = A, $S_{AT(e_1 e_2)} = 228,000$ psi

At r = B, $S_{BT(e_1 e_2)} = 176,000$ psi

At r = C, $S_{CT(e_1 e_2)} = 128,000$ psi

At r = D, $S_{DT(e_1 e_2)} = \ 98,500$ psi

c. Set sum of shrink stress and extrusion stress in each sleeve equal to the same constant, W. (Sum of shrink and extrusion stress in liner is 114,000 psi)

$$S_{(BT,\ 1,2,3)} + S_{BT(e_1 e_2)} = W$$

$$S_{(CT,2,3)} + S_{CT(e_1 e_2)} = W$$

$$S_{(DT,3)} + S_{DT(e_1 e_2)} = W$$

d. Substitute equations in 5a and values in 5b in 5c, and rearrange terms

$$0 + 8.48\ P_{L1} + 4.37\ P_{12} + 3.39\ P_{23} = 114,000$$

$$W - 5.89\ P_{L1} + 3.85\ P_{12} + 2.99\ P_{23} = 176,000$$

$$W + 0.00 \quad - 7.23\ P_{12} + 2.62\ P_{23} = 128,000$$

$$W + 0.00 \quad + 0.00 \quad - 6.10\ P_{23} = \ 98,500$$

e. Effect a determinant solution of 5d equations

Results are as follows:

$P_{L1} = 6,050$ psi

$P_{12} = 7,240$ psi

$P_{23} = 9,380$ psi

$W = 156,000$ psi

Maximum tangential stress at 1st, 2nd, and 3rd sleeve inner radii due to combined extrusion stresses is 156,000 psi

6. Tangential and Radial Stresses in Liner and Sleeve Assembly Due to Shrink Fitting

a. Determine liner stress distribution by use of interfacial pressures in 5e

$$S_{(LT,1,2,3)} = -\left[1+\frac{A^2}{r^2}\right]\left[\frac{B^2P_{L1}}{B^2-A^2}+\frac{C^2P_{12}}{C^2-A^2}+\frac{D^2P_{23}}{D^2-A^2}\right]$$

$$S_{(LT,1,2,3)} = -57,000 - \frac{185,000}{r^2} \qquad A \leq r \leq B$$

$$S_{(RT,1,2,3)} = -57,000 + \frac{185,000}{r^2}$$

b. Determine 1st sleeve stress distribution

$$S_{(LT,1,2,3)} = \frac{B^2P_{L1}}{C^2-B^2}\left[1+\frac{C^2}{r^2}\right] - \left[1+\frac{A^2}{r^2}\right]\left[\frac{C^2P_{12}}{C^2-A^2} - \frac{D^2P_{23}}{D^2-A^2}\right]$$

$$S_{(1T,1,2,3)} = -17,000 - \frac{14,600}{r^2} \qquad B \leq r \leq C$$

$$S_{(1T,1,2,3)} = -17,000 + \frac{14,600}{r^2}$$

c. Determine 2nd sleeve stress distribution

$$S_{(2T,2,3)} = \frac{C^2P_{12}}{D^2 - C^2}\left[1 + \frac{D^2}{r^2}\right] - \left[1 + \frac{A^2}{r^2}\right]\left[\frac{D^2P_{23}}{D^2 - A^2}\right]$$

$$S_{(2T,2,3)} = 6,600 + \frac{126,000}{r^2} \qquad C \leq r \leq D$$

$$S_{(2R,2,3)} = 6,600 + \frac{126,000}{r^2}$$

d. Determine 3rd sleeve stress distribution

$$S_{(3T,3)} = \frac{D^2P_{23}}{E^2 - D^2}\left[1 + \frac{E^2}{r^2}\right]$$

$$S_{(3T,3)} = 24,000 + \frac{264,000}{r^2} \qquad D \leq r \leq E$$

$$S_{(3R,3)} = 24,000 - \frac{264,000}{r^2}$$

Equations developed in section 6 are plotted in Figure 13 to show shrink stress as a function of radial distance in liner and each sleeve.

7. Tangential and Radial Stress in Liner and Each Sleeve due to Extrusion Pressure and Shrink Stress

a. Determine liner stress by adding appropriate equations in 4a to those in 6a

$$S_{(LT,1,2,3)ele2} = -48,000 + \frac{523,000}{r^2} \qquad A \leq r \leq B$$

$$S_{(LR,1,2,3)ele2} = -48,000 - \frac{523,000}{r^2}$$

b. Determine 1st sleeve stress by adding appropriate equations in 4a to those in 6b

$$S_{(1T,1,2,3)ele2} = -8,160 + \frac{693,000}{r^2} \qquad B \leq r \leq C$$

$$S_{(1R,1,2,3)ele2} = -8,160 - \frac{693,000}{r^2}$$

c. Determine 2nd sleeve stress by adding appropriate equations in 4a to those in 6c

$$S_{(2T,\,2,\,3)ele2} = 15,400 + \frac{834,000}{r^2} \qquad C \leq r \leq D$$

$$S_{(2R,\,2,\,3)ele2} = 15,400 - \frac{834,000}{r^2}$$

d. Determine 3rd sleeve stress by adding appropriate equations in 4a to those in 6d

$$S_{(3T,\,3)ele2} = 32,800 + \frac{972,000}{r^2} \qquad D \leq r \leq E$$

$$S_{(3R,\,3)ele2} = 32,800 - \frac{972,000}{r^2}$$

Equations developed in section 7 are plotted in Figure 13 to show peak stress due to extrusion pressure and shrink fitting as a function of radial distance, in liner and each sleeve

8. Maximum Permissible τ_o Value for Liner and Sleeves

a. τ_o must be less than or equal to the maximum working tensile stress of the material, S_o. The maximum working tensile stress of the H-13 steel is taken as 75% of the 0.2% offset yield strength. At 800°F, S_o = 180,000 psi

$$\tau_o \leq (0.707)(180,000) = 127,000 \text{ psi}$$

$$\tau_o \leq 127,000 \text{ psi}$$

9. Calculation of Peak τ_o Value in Liner and Each Sleeve under Combined Shrink Stresses and 210,000 psi Stem Pressure

a. Calculate peak τ_o value in liner and each sleeve by procedure in 19a

Peak τ_o value is at inner radius of each cylinder. Calculated values of τ_o for inner radius of liner and each sleeve are listed in Table VII.

Comparison of maximum permissible τ_o value calculated in section 8 with tabulated values shows that peak τ_o value on 1st sleeve is marginally high at a 16.7% extrusion pressure overload of 210,000 psi

10. Container Sleeve, and Container Stresses

TABLE VII

PEAK τ_o VALUES FOR LINER AND EACH SLEEVE, UNDER COMBINED SHRINK STRESS AND 210,000 PSI STEM PRESSURE, FOR THREE-SLEEVE ASSEMBLY

Part	Radius (r), in.	Tangential Stress (S_T), kpsi	Radial Stress (S_R), kpsi	Equivalent Shear Stress in Tension (τ_o), kpsi
Liner	1.80	114	-210	105
1st Sleeve	2.06	156	-171	134
2nd Sleeve	2.44	156	-125	119
3rd Sleeve	2.81	156	- 90.2	124

Container sleeve and container stresses will be identical to those calculated in section 21, for Design 1, since pressure on inner radius of container sleeve will be the same for both first and second liner-and-sleeve assembly designs. Container sleeve and container stress as a function of radial displacement, plotted in Figure 9, have been replotted in Figure 13 to provide a complete picture of the stresses present in the liner-three sleeve system.

11. <u>Liner-First Sleeve Interference, and Machining Dimensions</u>

a. Calculate interference between liner outer radius and 1st sleeve inner radius

$$\beta_{L1} = \frac{2B^3(C^2 - A^2)P_{L1}}{Y_{800}(B^2 - A^2)(C^2 - B^2)} = 0.0064 \text{ in.}$$

Interference at both 75°F and 800°F will be the same, as liner and 1st sleeve have the same thermal expansion coefficient.

At 75°F, liner outer radius is 2.0650 in.

At 75°F, 1st sleeve inner radius will be 2.0650 - 0.0064 = 2.0586 in.

b. Calculate 1st sleeve shrink-fitting temperature for liner at 75°F, allowing 0.0050 in. radial clearance when 1st sleeve is heated to fitting temperature

Liner-1st sleeve interference is 0.0064 in. Allowing 0.0050 in. clearance between sleeves when 1st sleeve is heated requires a total 0.0114 in. expansion of 1st sleeve inner radius

$$\Delta_{t-75} = \frac{B_t - B_{75}}{\alpha B_{75}} = 770°F$$

$$t = 770°F + 75°F = 845°F$$

c. Calculate expansion of 1st sleeve outer radius, to determine its stressed dimension at 75°F

$$U_{1C,1} = \frac{(B^2 - A^2)\beta_{L1}}{B(C^2 - A^2)} = 0.0011 \text{ in.}$$

Outer radius of 1st sleeve, at 75°F, is 2.4389 in.

Expanded outer radius of 1st sleeve, at 75°F, is 2.4400 in.

12. <u>First-Second Sleeve Interference and Machining Dimensions</u>

a. Calculate interference between 1st sleeve stressed outer radius and 2nd sleeve inner radius

$$\beta_{12} = \frac{2C^3(D^2 - A^2)P_{12}}{Y_{800}\,(C^2 - A^2)(D^2 - C^2)} = 0.0055 \text{ in.}$$

At 75°F, stressed 1st sleeve outer radius is 2.4400 in.

At 75°F, 2nd sleeve inner radius will be 2.4345 in.

b. Calculate 2nd sleeve shrink fitting temperature for 1st sleeve at 75°F, allowing 0.0060 in. radial clearance when 2nd sleeve is heated to fitting temperature

First sleeve-second sleeve interference is 0.0055 in. Allowing 0.0060 in. clearance between sleeves when 2nd sleeve is heated requires a total 0.0115 in. expansion of 2nd sleeve inner radius.

$$\Delta t_{t-75} = \frac{C_t - C_{75}}{\alpha C_{75}} = 655°F$$

$$t = 655°F = 75°F = 730°F$$

c. Calculate expansion of 2nd sleeve outer radius to determine its stressed dimension at 75°F

$$U_{2D,\,2} = \frac{(C^2 - A^2)\beta_{12}}{C(D^2 - A^2)} = 0.0013 \text{ in.}$$

Outer radius of 2nd sleeve, at 75°F, is 2.8087 in.

Expanded outer radius of 2nd sleeve, at 75°F, is 2.8100 in.

13. Second-Third Sleeve Interference, and Machining Dimensions

a. Calculate interference between 2nd sleeve stressed outer radius and 3rd sleeve inner radius

$$\beta_{23} = \frac{2D^3(E^2 - A^2)P_{23}}{Y_{800}(D^2 - A^2)(E^2 - D^2)} = 0.0085 \text{ in.}$$

At 75°F, stressed 2nd sleeve outer radius is 2.8100 in.

At 75°F, 3rd sleeve inner radius will be 2.8015 in.

b. Calculate 3rd sleeve shrink fitting temperature for 2nd sleeve at 75°F, allowing 0.0060 in. clearance when 3rd sleeve is heated to fitting temperature

Second sleeve-third sleeve interference is 0.0085 in. Allowing 0.0060 in. clearance between sleeves when 3rd sleeve is heated requires a total 0.0145 in. expansion of 3rd sleeve inner radius.

$$\Delta t_{t-75} = \frac{D_t - D_{75}}{\alpha D_{75}} = 720°F$$

$$t = 720°F + 75°F = 795°F$$

c. Calculate expansion of 3rd sleeve outer radius to determine its unstressed dimension at 75°F

$$U_{3E,3} = \frac{(D^2 - A^2)\beta_{23}}{C(E^2 - A^2)} = 0.0018 \text{ in.}$$

Machined outer radius of 3rd sleeve, at 75°F, should be 0.0018 + 0.0003 = 0.0021 in. less than container sleeve inner radius to permit a 0.0001 - 0.0005 in. clearance between 3rd sleeve outer radius and container sleeve inner radius. Container sleeve inner radius will be 3.3100 in. at 75°F. Stressed outer radius of 3rd sleeve will be 3.3089 in.

Unstressed outer radius of 3rd sleeve will be 3.3068 in.

14. <u>Contraction of Liner Inner Radius due to Shrink Fit of First, Second, and Third Sleeves</u>

a. Determine liner inner radius contraction in terms of tangential stress generated at liner inner radius by shrink fit of 1st, 2nd, and 3rd sleeves

$$U_{LA,1,2,3} = \frac{(114{,}000)A}{Y_{800}} = 0.0078 \text{ in.}$$

15. <u>Calculation of Required Force and Pressure for Separation of Liner-Sleeve Assembly</u>

a. General Approach

Sleeves cannot be separated by differential heating for the same reasons discussed in section 20a, for Design 1, and, therefore, must be pressed off one another. As in 20a, outer sleeve will be removed first.

The calculation of sleeve removal force and pressure is considerably simplified, in this case, because liner and sleeves have the same thermal expansion and elastic modulus coefficients. This makes it possible to disregard sleeve temperature in the calculation, since interference of sleeves, and hence removal pressure, does not appreciably change with a change in temperature.

b. Calculate sleeve removal force and removal pressure by use of interfacial pressure calculated in 5d and equations in 20b.

Values of required removal force and pressure for each sleeve are given in Table VIII.

TABLE VIII

REQUIRED REMOVAL FORCE AND PRESSURE FOR EACH SLEEVE IN THREE-SLEEVE ASSEMBLY

Sleeve No.	Interfacial Pressure, psi	Removal Force, tons	Removal Pressure, psi
3	9,380	167	40,400
2	7,240	112	43,000
1	6,050	79	29,200

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